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Volume II

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TENSILE PROPERTIES AND FRACTURE TOUGHNESS
OF
6Al-4V TITANIUM

C. E. Hartbower
W. G. Reuter
P. P. Crimmins

Aerojet-General Corporation
Sacramento, California 95813

Technical Report AFML-TR-68-163, Volume II
March 1969

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Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by Aerojet-General Corporation, Sacramento, California, under USAF Contract F33615-67-C-1358. The contract was initiated under Project No. 7381, a Materials Applications, Task No. 738106, "Engineering and Design Data", and administered under the direction of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, with Mr. A. W. Gunderson (MAAE) as Project Engineer.

The study program at the Aerojet-General Corporation was performed under the management of P. P. Crimmins, Manager of Structural Metals Research and Development, Materials Advanced Technology Department, with C. E. Hartbower as Principal Investigator.

The authors gratefully acknowledge the many helpful comments and suggestions made by A. W. Gunderson of the Air Force Materials Laboratory during the conduct of this program. The authors are also indebted to Mrs. Mary W. Fong of the Aerojet Computing Sciences Division for her assistance in statistical analysis of the data.

This report covers the period April 1968 to March 1969. The report was submitted by the authors in March 1969.

This technical report has been reviewed and approved.

A. Olevitch

A. Olevitch
Chief, Materials Engineering Branch
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ABSTRACT

Material taken from 6Al-4V titanium rocket motor cases was tested with precrack Charpy impact specimens to evaluate the following as factors affecting plane-stress crack toughness and/or chamber performance: (1) anisotropy and inhomogeneity, (2) forging practice (die, ring-roll and extrusion), (3) interstitial-element chemistry, and (4) test temperature. The material was obtained from 14 hydroburst Minuteman chambers, nine of which were premature-proof-test failures, four were successfully hydroburst chambers, and one failed after 11 proof-test cycles. Material sampling included the immediate vicinity of fracture origins in an attempt to correlate fracture toughness and chamber performance.

Significant differences in precrack Charpy W/A values were found between (1) the two chamber wall thicknesses tested, (2) forgings, (3) forging practices and (4) test temperatures. Some individual cylinders appeared to have a marked difference in W/A value from end-to-end in both the membrane wall and the reinforced sections. However, analysis of variance did not show a significant difference from end-to-end of the cylinders. Multiple regression and correlation analysis indicate carbon and oxygen to have a significant effect on toughness in the Minuteman chemistry. In four out of six chambers with secondary fractures in the hoop direction, the W/A values in the hoop direction were either very low or lower than those in the axial direction. Variable response to temperature and forging-to-forging differences necessitate fracture testing of every forging in critical service applications.

Relationships between fracture toughness and chamber performance were evaluated. Because of the relatively low plane-stress crack toughness of the material, Irwin's leak-before-burst criterion was not met. Thus, the chambers failed as a result of plane-strain pop-in. In chambers with semi-elliptical surface flaws, an attempt was made to predict the hoop stress at failure on the basis of the measured flaw dimensions and the mean K_{Ic} value as determined from 109 forgings in Phase I; viz, 39 ksi-in.^{1/2} with a standard deviation of 1.6 ksi-in.^{1/2}. The prediction was in close agreement in five out of six cases based on a two-sigma spread in K_{Ic} value.

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SECTION I

INTRODUCTION

Phase I, a MIL-HDBK-5 data collection program, has been completed to provide room- and elevated-temperature-tensile and fracture-toughness data on 6Al-4V titanium at a 0.2% offset yield strength of approximately 160 ksi. The data were presented in Technical Report AFML-TR-68-163, Volume I, September 1968, entitled "Tensile Properties and Fracture Toughness of 6Al-4V Titanium" (378 pages, including five appendices). The material was from 44- and 52-in.-dia second-stage Minuteman rocket-motor cases. The elevated-temperature tensile data were for temperatures up to 330°F. The fracture toughness data included plane-strain K_{Ic} from 540 part-through-crack (PTC) tensile tests of 109 forgings, plane-stress K_c from 75 fatigue-precracked center-notch (CN) tensile tests of 18 forgings, and precrack Charpy slow-bend and impact tests of specimens cut from fractured CN-tensile specimens. The 18 forgings were from nine hydroburst chambers, four of which were premature proof-test failures and five were successfully hydroburst in the Minuteman development program.

The uniaxial tensile-data means were determined for each temperature and plots of percent-of-room temperature tensile-properties versus temperature were constructed for input to MIL-HDBK-5. For room temperature, the A-basis values of ultimate strength, yield strength, and percent elongation were 166.3 ksi, 153.0 ksi, and 10.2%, respectively; the B-basis values were 168.8 ksi and 156.4 ksi, respectively. The PTC-tensile specimens were oriented in the hoop direction; i.e., the flaw was propagating in the axial direction of the cylinder. The PTC-tensile K_{Ic} data were examined for the variation in fracture toughness attributable to between-forging, between-heat, and between-test-laboratory variability, first on the basis of engineering plots of data from individual laboratories, forgings, billets, and heats, and then by statistical-analysis techniques. Based on the engineering plots, tests of multiple forgings from a single heat of titanium and multiple forgings from a single billet of titanium revealed differences in K_{Ic} from forging to forging when the surface precrack was deep (approximately 50% of specimen thickness) but little or no difference in K_{Ic} with a shallow crack (approximately 25% of specimen thickness). Comparisons between laboratories revealed differences between test results in some forgings but not all. Based on statistical analysis, a significant difference was indicated between K_{Ic} values at the two crack depths investigated. However, statistically, there was not a significant difference between forgings or between heats with shallow cracks, whereas, with deeper cracks there was a significant difference between heats but not a significant difference between forgings. When the data from the shallow cracks were pooled and plotted on probability paper, the population mean was 39.1 ksi-in.^{1/2} with a standard deviation of 1.6 ksi-in.^{1/2}. On the basis of all 540 tests, treated as a non-normal distribution, the A-basis value was 30.6 ksi-in.^{1/2} and the B-basis value was 35.2 ksi-in.^{1/2}.

I, Introduction (cont.)

The CN-tensile specimens were oriented in the axial direction; i.e., the flaw was propagating in the hoop direction. The CN-tensile K_{Ic} values ranged from 31.2 to 74.6 ksi-in.^{1/2}; thus, the K_{Ic} values in some forgings were appreciably higher than any values measured in the PTC-tensile tests of 109 forgings tested with a different crack orientation. Precrack Charpy slow-bend W/A values were found to provide a good estimate of the CN-tensile K_{Ic} values through the relationship

$$K_{Ic} = 170 (W/A)_{PCSB} + 16200$$

where $(W/A)_{PCSB}$ is the precrack Charpy slow-bend value in in.-lb/in.². The CN-tensile K_c data based on the onset of crack instability as determined by an acoustical technique ranged from 71 to 137 ksi-in.^{1/2} for the 18 forgings tested. Precrack Charpy impact W/A values were found to provide a good estimate of the CN-tensile K_c values through the relationship

$$K_c = 100 (W/A)_{PCI} + 6700$$

In the Phase I data collection, the orientation of the CN-tensile specimen was such that the crack was propagating in the chamber hoop direction; i.e., at 90 degrees to the principal direction of fracture in the premature proof-test failures of full-scale chambers. No attempt was made in Phase I of the data collection to correlate the laboratory test results with full-scale Minuteman chamber performance because (1) anisotropy in the forgings precluded correlation between CN-notch tensile specimens oriented for fracture in the hoop direction and chamber performance with fracture in the axial direction; and (2) reliable axial-crack-propagation CN-tensile data could not be obtained in the reinforced (increased-thickness) region containing the chamber girth welds where fracture usually initiated in premature proof-test failures of full-scale chambers. Thus, Phase II, as described in the following paragraphs, sought correlation with full-scale chamber performance using the fatigue-precracked Charpy impact test specimen.

The material for Phase II of the data collection was obtained from 14 full-scale hydroburst Minuteman chambers, including eight of the nine chambers investigated in Phase I. Nine of the 14 chambers were premature proof-test failures, four were successfully hydroburst chambers and one was cycled 11 times before it failed in proof test. Closures, skirts, and cylinders from the 14 chambers provided data on 69 forgings, involving three forging practices; viz, die, ring roll and extrusion. The small size of the precrack Charpy specimen permitted testing with the specimen oriented so as to fracture in the chamber-axial direction. The Charpy specimens were located in both the 0.19-in.-thick reinforced section adjacent to the girth

I, Introduction (cont.)

welds and the 0.10-in.-thick walls on either side of the girth-weld reinforced sections. Selected forgings in each chamber were tested at -40, RT, 200, and 320°F. Particular attention was directed to the material in the immediate vicinity of the fracture origin in each of the chambers that failed in proof test.

The objectives of the Phase II data collection were as follows:

- (1) correlation of fracture toughness and chamber performance; (2) evaluation of anisotropy and inhomogeneity in chamber components as factors affecting chamber performance; (3) evaluation of forging practice (metal processing) as a factor affecting crack toughness; (4) evaluation of chemistry as a factor affecting crack toughness; (5) evaluation of test reproducibility (between Phases I and II and replicate tests); and (6) evaluation of the effect of temperature as an environmental factor affecting crack toughness.

SECTION II

TEST PROCEDURE

A. MATERIAL SAMPLING

Phase I of this study indicated a variation in toughness both with crack direction (anisotropy) and with specimen location in a given forging (inhomogeneity). Thus, in Phase II of the data collection, the material sampling procedure was designed to determine the extent of variability from location to location in a given forging as well as to evaluate toughness in the immediate vicinity of the fracture origin. Because fracture in the full-scale chambers usually propagated in the chamber-axial direction, and because several of the premature failures initiated in the reinforced section at a girth weld, it was necessary to machine the Charpy specimens in the hoop direction (crack propagating in the chamber-axial direction) and in the immediate vicinity of the girth welds. The combination of (1) dimensions of the reinforced wall at the girth welds, (2) the inherent curvature in the material cut from the 52-in.-dia chamber, and (3) the direction of fracture in the full-scale chambers, individually and collectively, precluded the use of specimens larger than the precrack Charpy. Obviously, if the 3-in.-wide center-notched panel (used in Phase I of the collection) were machined with the notch centered on the weld reinforcement, the $2a_0$ crack length would have exceeded the width of the reinforced section and, moreover, the test section in the path of fracture would have been of variable thickness. Taking these limitations into account, the widest CN-tensile that could have been used to test the reinforced section of the Minuteman girth welds was approximately 1 in. Also, the curvature in the CN-tensile would have produced a bending stress that would have been a complication in calculating the fracture toughness; and, furthermore, if the material had been heat-straightened preparatory to testing, the properties of the material could have been substantially changed by the plastic deformation introduced in the flattening operation.

In premature proof-test failures originating from girth-weld reinforced sections, the crack origin was often found to be transverse to the weld and located in the base metal adjacent to the weld, bounded on one side by weld heat-affected zone and on the other by parent metal. In other words, the initiating cracks were usually outside the weld fusion zone but close enough to the weld to extend partially into the weld heat-affected zone.

The size of the Charpy specimen allowed it to be positioned in the reinforced section with the V-notch in the weld metal and the fatigue precrack extending into the heat-affected base metal. Figure 1 shows the position of the Charpy in the reinforced section adjacent to a girth weld; Figure 1 also shows the macrostructure as contained in a typical specimen. Note the location of the V-notch and fatigue precrack with respect to the darkly etched weld heat-affected zone. In an occasional test specimen, because of irregularities in the width of the weld deposit, the weld metal extended somewhat below the fatigue precrack; in such cases, both the fracture appearance and the magnitude of the toughness values made the discrepancy apparent.

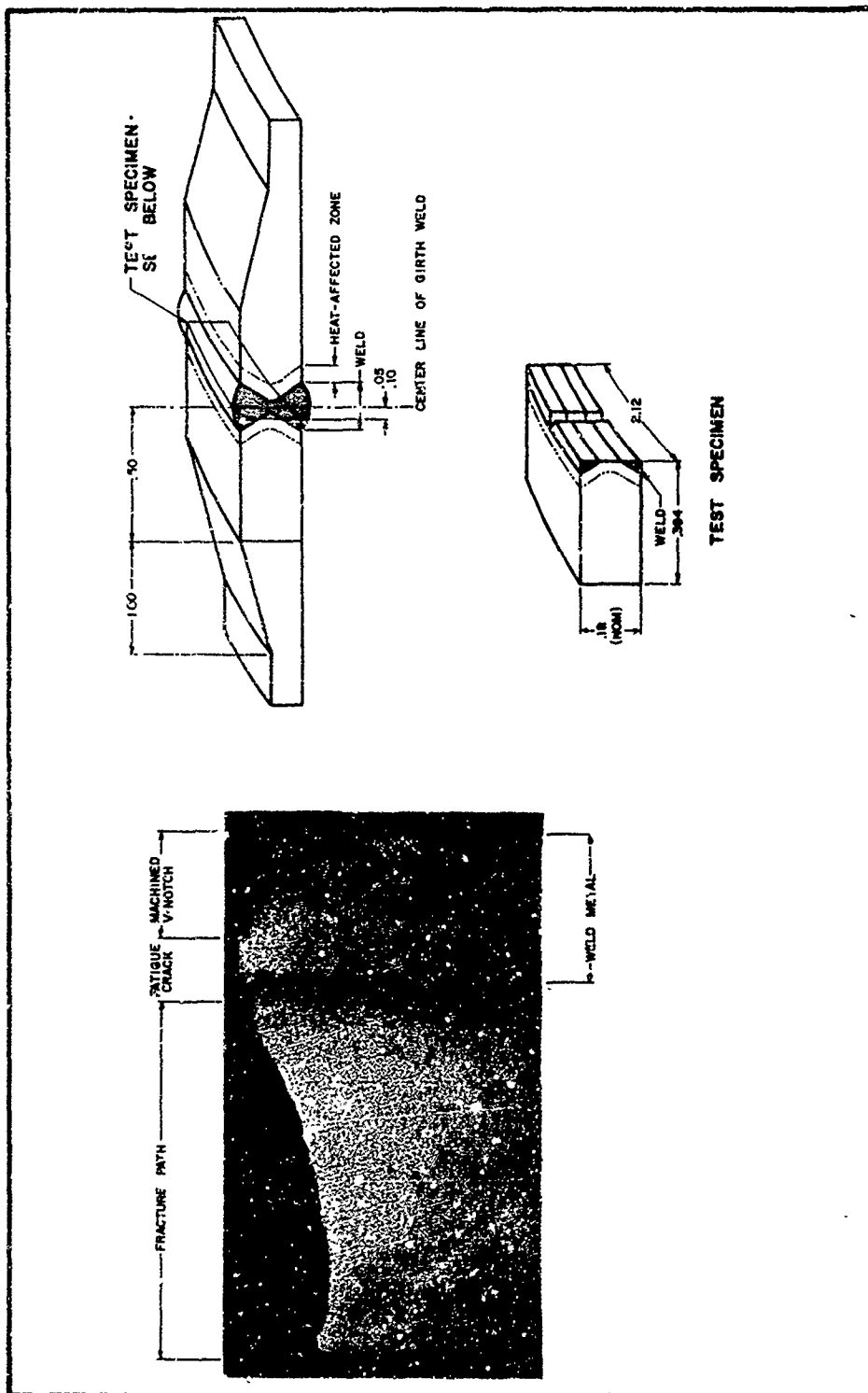


Figure 1. Location of Precrack Charpy Impact Specimens in Reinforced Section at Chamber Girth Welds

II, A, Material Sampling (cont.)

From Figures 2 and 3 (44-in. and 52-in.-dia chambers), it will be seen that one major difference between the 44-in.-dia and the 52-in.-dia chambers was in the interstage connection. In the 44-in.-dia chamber, the skirts were an integral part of the closure die-forgings; whereas, in the 52-in.-dia chamber, the skirts were ring-rolled forgings joined to the closure die-forgings by welding. The cylinders in the 52-in.-dia chambers were, in each case, extrusions; whereas, in the 44-in.-dia chambers, they were sometimes extrusions and sometimes ring-rolled forgings. In all chambers, the cylinders were welded to the forward and aft closures. The adapter, or flange, in both the 44-in.-dia and the 52-in.-dia chambers is an integral part of the closure die-forgings.

The general test plan called for fracture tests of each forging type. In some chambers, material was not available from all components. Tables I and II show the test plan for the chambers. Wherever possible, the specimens to be tested over a range of temperature were machined from material in the immediate vicinity of the fracture origin. Figure 4 schematically shows the location of test specimens in the 44-in. and 52-in.-dia chambers. In some chambers, secondary fracturing occurred in the hoop direction. Additional specimens were taken from these chambers as close as possible to the intersection of the main (axial) and the secondary (hoop) fracture paths; the additional specimens were machined to test with crack propagation in the axial and hoop directions.

The elevated test temperatures were selected to coincide with the temperatures used in hydroburst testing. Note that these temperatures, together with a -40°F test, resulted in approximately uniform increments of 120°F; viz, -40, RT, 200, and 320°F.

B. PRECRACK CHARPY IMPACT TEST

The precrack Charpy test* is similar to the standard V-notch Charpy impact test, except that (1) the machined notch in the specimen is sharpened by fatigue cracking, (2) the width of the test piece is generally the material thickness (the width may be as small as 0.03 in. in testing high-strength sheet and as large as 0.8 in., a limit imposed by the design of most impact-testing machines) and (3) the test result is expressed in terms of energy absorbed per unit of fracture area (W/A - in.-lb/in.²).

The precracking of Charpy specimens is best accomplished by fatigue cycling. A special machine is commercially available for precracking Charpy specimens. Crack depths are normally held to approximately 0.025 in., but may vary considerably without significantly affecting the results. Since the

*Hartbower, C. E. and Orner, G. M.; Welding Journal, Vol 36(11), p.494-s (Nov 1957); ASTM Proceedings, Vol 58(1958), p.623; Welding Journal, Vol 33(4), p.147-s (Apr 1960); Ibid. Vol 40(9), p.405-s (Sept 1961); ASD-TDR-62-868, June 1963.

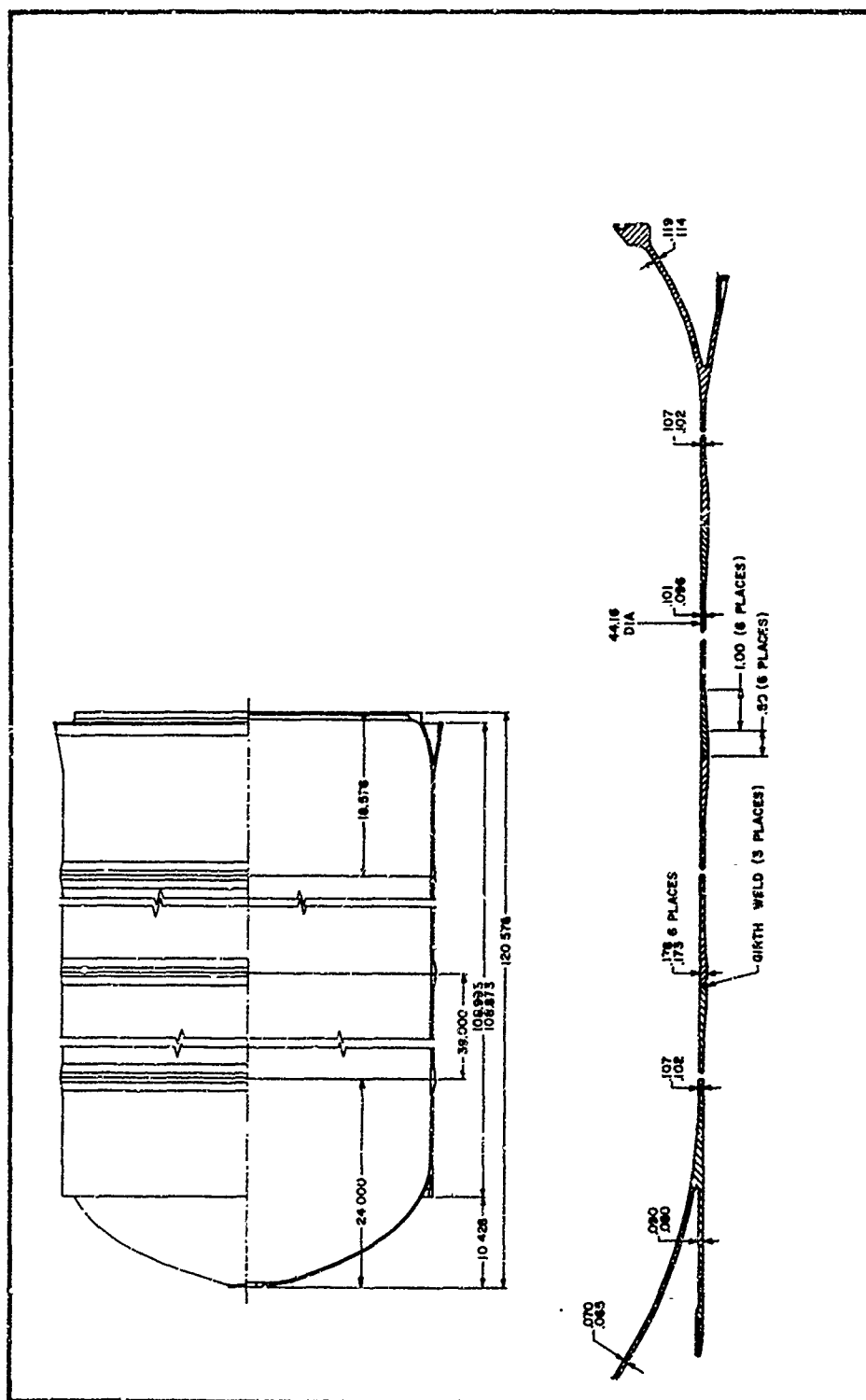


Figure 2. Design of the 44-In.-dia Second-Stage Minuteman Chamber

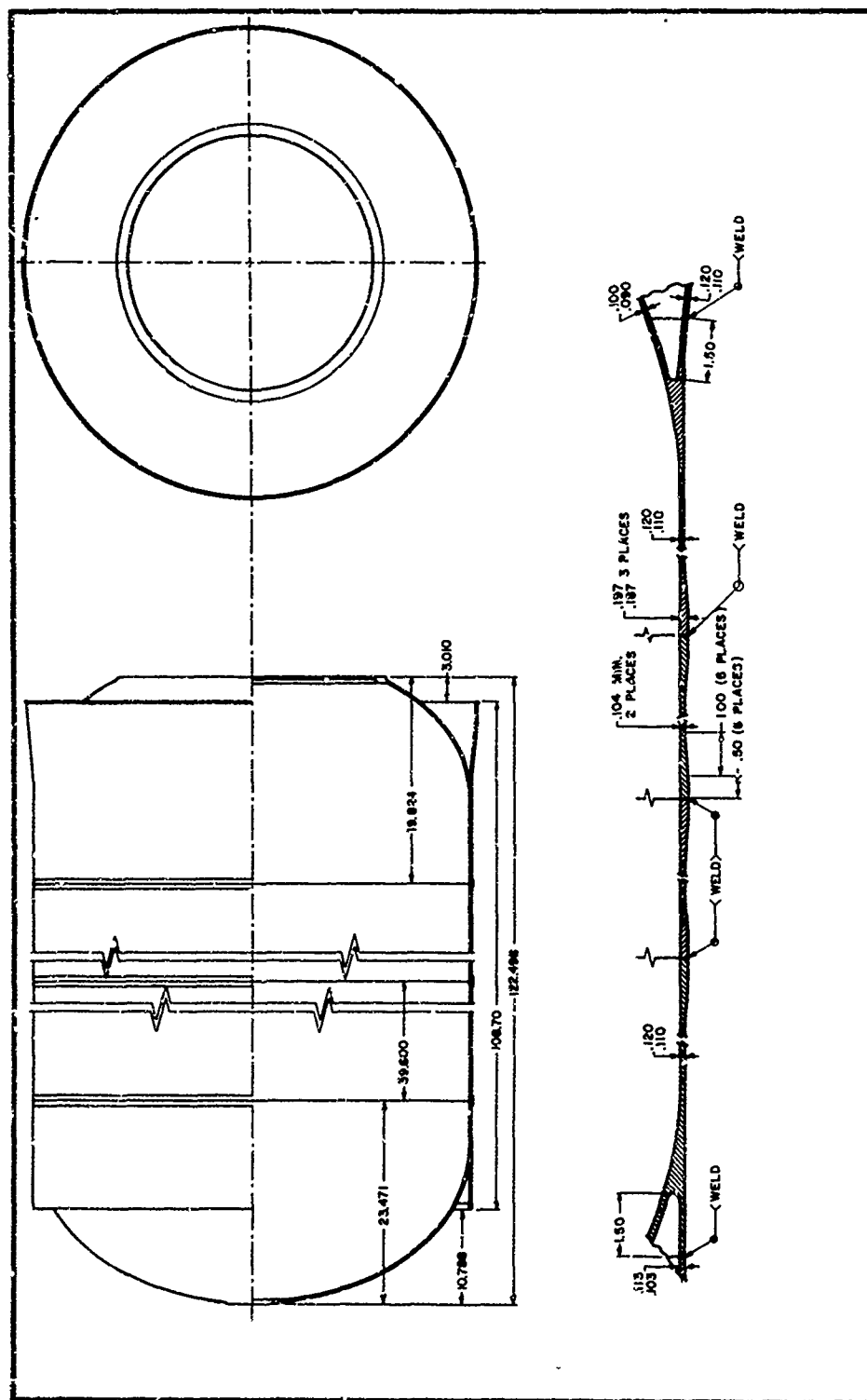


Figure 3. Design of the 52-in.-dia Second-Stage Minuteman Chamber

TABLE I

TEST PLAN FOR MINUTEMAN CHAMBERS
R26, R41, BL26 and 2191456

| Chamber Component | Specimen Location | Total Specimens | Test Temperature, °F | | | |
|---------------------------------------|----------------------|--------------------|----------------------|----|-----|-----|
| | | | -40 | RT | 200 | 320 |
| <u>Chambers R26, R41, and 2191456</u> | | | | | | |
| Dome | (a) | 12 | 3 | 3 | 3 | 3 |
| Adapters - Fwd | (a) | 12 | 3 | 3 | 3 | 3 |
| | Aft | 12 | 3 | 3 | 3 | 3 |
| Cylinders - Fwd | (a) | 12 | 3 | 3 | 3 | 3 |
| | Aft | 12 | 3 | 3 | 3 | 3 |
| <u>Chamber BL26</u> | | | | | | |
| Adapter - Fwd | At G1 weld | 4 | | 4 | | |
| | thin wall | 12 | 2 | 3 | 3 | 2 |
| Aft | At G3 weld | 4 | | 4 | | |
| | thin wall | 12 | 3 | 3 | 3 | 3 |
| Cylinders - Fwd | At G1 weld | 4 | | 4 | | |
| | thin wall | 4 | | 4 | | |
| Aft | At G3 weld | 4 | | 4 | | |
| | thin wall | 12 | 3 | 3 | 3 | 3 |

*Exact location within the chamber component not known.

TABLE II

TEST PLAN FOR MINUTEMAN CHAMBERS

R490, R369, R512, R516, R543, 673078, 673095, 673122, 674514, and 2192109

| <u>Chamber Component</u> | <u>Specimen Location</u> | <u>Total Specimens</u> | <u>Test Temperature, °F</u> | | | |
|------------------------------|------------------------------|----------------------------|-----------------------------|-----------|------------|------------|
| | | | <u>-40</u> | <u>RT</u> | <u>200</u> | <u>320</u> |
| Done | - | 12 | 3 | 3 | 3 | 3 |
| Adapter - | Fwd | At G1 weld | 3 | 3 | 3 | 3 |
| | | thin wall | | 3 | | |
| | Aft | At G3 weld | 3 | 3 | 3 | 3 |
| | | thin wall | | 3 | | |
| Cylinders - | Fwd | At G1 weld | | 3 | | |
| | | thin wall | | 3 | | |
| | | At G2 weld | 3 | 3 | 3 | 3 |
| | | thin wall | | 3 | | |
| | Aft | At G2 weld | 3 | 3 | 3 | 3 |
| | | thin wall | | 3 | | |
| Skirts - | | At G3 weld | | 3 | | |
| | | thin wall | | 3 | | |
| | Fwd | - | | 3 | | |
| | Aft | - | | 3 | | |
| Weld (R490 only) | - | 12 | 3 | 3 | 3 | 3 |

Note: In all cases, three specimens were fabricated so the flaw was growing in the hoop direction. These specimens were located adjacent to one of the sets of three taken from the thin wall of the cylinders.

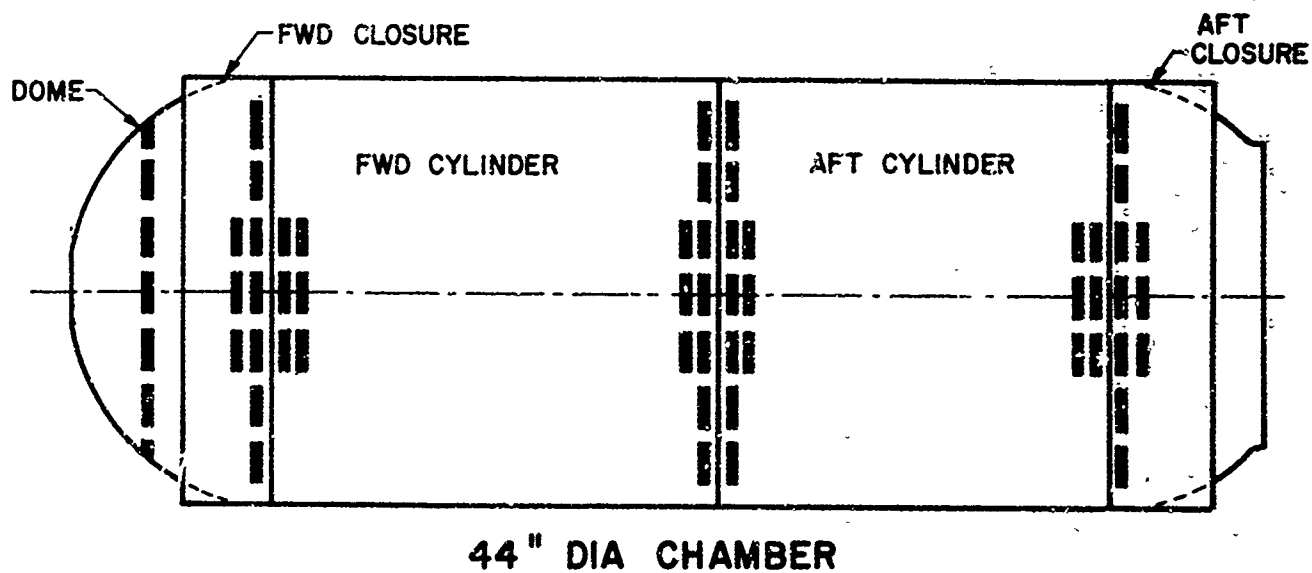
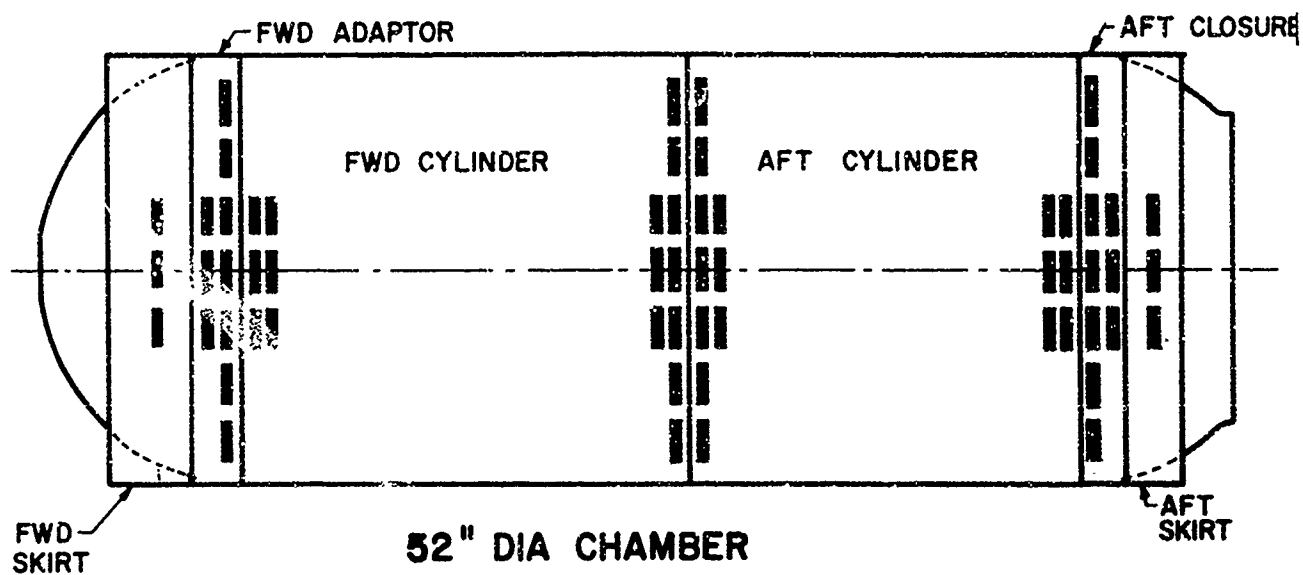


Figure 4. Schematic of Specimen Location in the 44-in.-dia and 52-in.-dia Chambers

II, B, Precrack Charpy Impact Test (cont.)

test results are expressed in terms of work divided by fracture area, the lower energy values resulting from more deeply cracked specimens are compensated by the decrease in fracture area. Thus, within practical limits, the measurement of W/A is largely insensitive to precrack depth.

Impact testing precracked specimens is conducted using standard Charpy techniques; however, because of the low energy values often encountered in precracked high-strength materials, a sub-size impact-testing machine is used which reads in small energy increments. This machine and the precracking machine are shown in Figure 5.

In the MIL-HDBK-5 data collection described in this report, precracking was accomplished in approximately 3 min (at 1725 cpm) using a fatigue precracking machine. Loading was in tension-zero-tension, and the outer fiber stress was nominally 45 ksi. The precrack Charpy specimens were tested in a MANLABS CIM-24 Impact Tester. Impact testing at room and elevated temperature was conducted using standard Charpy techniques. The elevated temperatures were obtained in a bath of silicone-base oil, the room temperature tests were made in air, and the -40°F temperature was obtained in acetone and dry ice. The test pieces were soaked for a minimum of 15 min within $\pm 2^{\circ}\text{F}$ of the desired temperature; the maximum time for testing a specimen was 3 sec.

C. PLANE STRESS (K_{IC}) CRACK TOUGHNESS MEASUREMENT

There is as yet no generally accepted, standardized test for measuring the crack toughness of sheet materials. Most of the work done up to this time has been based on linear-elastic fracture-mechanics concepts as developed by Irwin and the ASTM Special Committee on Fracture Testing of High Strength Metallic Materials*.

In the early work of the ASTM Committee (now designated E24), emphasis was placed on K_{IC} measurements and, after the necessity for using fatigue cracked specimens was realized and improved methods for measuring crack growth came into use, such as displacement gages and electrical potential measurements, reasonably satisfactory procedures for K_{IC} measurements were developed. The emphasis on plane-stress (K_{IC}) crack toughness was the direct result of problems with premature failures in thin-skinned, roll-and-weld missiles that were being built at that time. The goal was a critical defect size of at least twice the thickness; it was found that when this criterion was met, a satisfactory service performance was generally assured**.

*"Fracture Testing of High Strength Sheet Materials," ASTM Bulletin, January 1960, pp 29-40, and February 1960, pp 18-28; also "The Slow Growth and Rapid Propagation of Cracks," Materials Research Standards, May 1961, pp 389-393.

**Irwin, G. R., "Structural Aspects of Brittle Fracture," Applied Materials Research, Vol. 3, pp 65, April 1964.

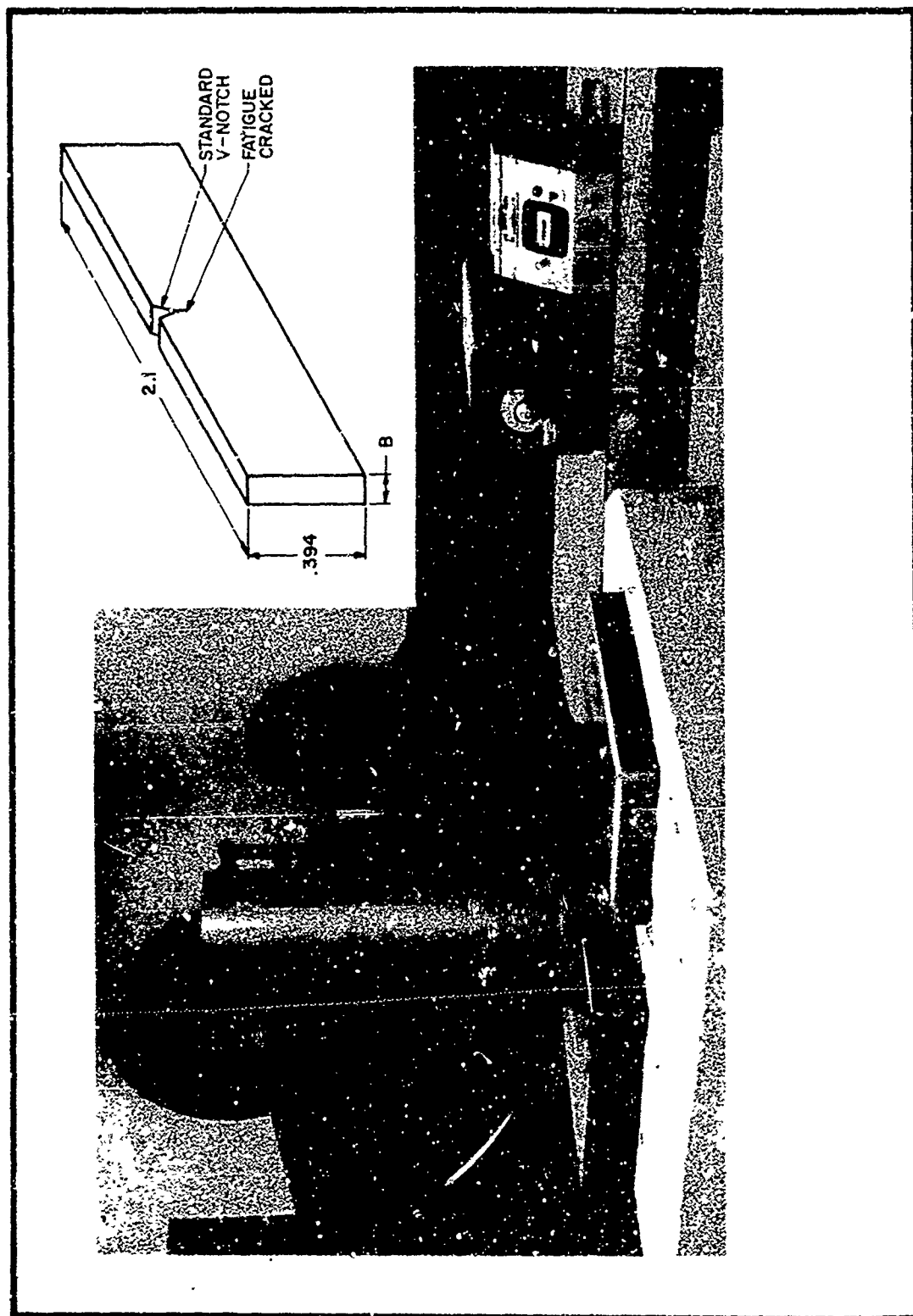


Figure 5. Fatigue-Precracking and Impact-Testing Machines
for the Precrack Charpy Test (Specimen Superimposed)

II, C, Plane Stress (K_C) Crack Toughness Measurement (cont.)

As the plane-stress fracture toughness studies progressed, experimental data were obtained by various investigators showing a marked variation in K_C with material thickness. From this, it became apparent that the applicability of K_C results would be markedly dependent upon the thickness of the material and might be significant only at the specific thickness of the test specimen. This limited applicability of the plane-stress measurement, together with the realization that the K_{IC} values as determined from thick specimens were generally applicable regardless of thickness, were predominant factors in the switch to plane-strain fracture toughness testing which has dominated E24 Committee activities over the last three years or so.

Unfortunately, because of the later emphasis on plane-strain crack toughness, many people appear to have concluded that the K_C measurement is less meaningful than K_{IC} and, therefore, have concentrated on the plane-strain K_{IC} measurement in lieu of K_C crack toughness measurements, even for sheet applications. This trend has been strengthened by the realization that although plane-strain fracture conditions are most nearly approached in thick sections, this condition may be approached by shallow surface cracks propagating in the thickness direction of sheet materials. However, as will be shown in following paragraphs, in sheet thicknesses and even in some plate materials, exclusive use of the K_{IC} crack-toughness measurement leads to an overly conservative design for some service applications.

Irwin has pointed out that there are two lines of defense against crack propagation. The first line of defense is based on an adequate K_{IC} crack toughness. When the crack is spreading as an embedded crack, if the stresses are high, very small cracks must be regarded as dangerous. Thus, the first line of defense is based on minimizing the working stresses and stress concentrations in design, improving nondestructive inspection to eliminate small cracks and notches, and using material of optimum K_{IC} crack toughness. Sometimes, on reaching plane-strain instability (pop-in), the crack extension across the sheet will be arrested by an increasing resistance to crack propagation under plane-stress conditions. This increasing resistance to propagation as the crack spreads laterally in the sheet is associated with a fracture-appearance transition as the fracture surface changes from square in the pop-in region to an increasing percentage of slant fracture as the plane-stress condition is approached.

The practical importance of the plane-stress K_C crack toughness measurement is further substantiated by the fact that in some materials and material conditions, there is no correlation between the K_C and K_{IC} measurements. Some investigators have been willing to focus their attention on K_{IC} to the exclusion of K_C , based on the assumption that a material with low K_{IC} will also have low K_C values. Thermal-mechanically treated 0.25C H-11 steel is a notable example where K_{IC} is relatively low and invariant, whereas K_C varies over a wide range*.

*Gerberich, W. W., "A Discussion of Slow Crack Growth Associated with Plane-Strain Instability," ASTM Transactions, Vol. 59(4), December 1966.

II, C, Plane Stress (K_C) Crack Toughness Measurement (cont.)

In work by Kaufman of the Alcoa Research Laboratories*, it has been shown that even in 1-in.-thick, wide-plate, through-crack, center-notch tension tests, there was stable, slow crack growth after plane-strain pop-in, with K_C controlling the ultimate fracture of the panels. In other words, the thick plate demonstrated considerably more crack toughness than was indicated by the plane-strain stress-intensity factor. In the Alcoa study, ten combinations of alloy and temper were investigated using 20-in.-wide, center-notch tension panels, single-edge-notch specimens and notch-bend specimens. Only the large center-notch panels provided information on the critical instability of the alloys in terms of K_C for the thickness tested. This is an important observation because, of the eight alloy compositions tested, all except two exhibited values of K_C considerably higher than K_{IC} in the cracking direction tested. As a result, the use of the K_{IC} value in design could be overly conservative in materials where mixed-mode fracture prevails and where leak-before-burst is an acceptable service condition**. If fatigue-sharpened notches had been used in the study rather than machined sharp notches, an even greater difference between the K_{IC} and K_C values might have been expected (i.e., lower K_{IC} values).

Similar results were obtained in studies of eight candidate alloys for the supersonic commercial transport (SST)***. In 1-in.-thick panels, slow crack growth of as much as 1.1 in. occurred before the crack reached critical length. The data in Table III were obtained from 9-in.-wide, center-notch panels of 1-in.-thick plate, tested at room temperature (the fracture toughness values include a plastic-zone correction). The values of percent shear (slant) were measured in the fracture surfaces at a distance of 2 in. from the outside edge of the panel. The critical crack length was determined by motion-picture photography. Pop-in was detected by crack-opening displacement and by accelerometer.

Thus, it has been shown that a variety of materials are capable of stable slow crack growth after plane-strain pop-in, even in plate thicknesses up to 1 in. In such materials, rapid (unstable) crack propagation occurs only

*Kaufman, J.G., Nelson, F.G. Jr., and Holt, M., "Fracture Toughness of Aluminum Alloy Plate Determined with Center-Notch Tension, Single-Edge-Notch Tension and Notch-Gond Tests," presented at the National Symposium on Fracture Mechanics, Lehigh University, June 20, 1967.

**Obviously, in some service applications, say a fuel tank, one cannot tolerate a leak (pop-in through the thickness) and, therefore, plane-strain fracture toughness is the only consideration.

***Thick Section Fracture Toughness, Air Force Materials Laboratory Tech. Doc. Report No. ML-TDR-64-236, October 1964, prepared under Contract AF 33(657) 11461 by Boeing-North American in a joint venture.

TABLE III

CENTER-NOTCH-PANEL TESTS OF 1-IN.-THICK SST MATERIALS

| Alloy | 1/2 Crack Length, in. | | Slant Fracture, % | Fracture Toughness, ksi-in. ^{1/2} | |
|---------------|-----------------------|----------|----------------------|--|----------------|
| | Initial | Critical | | K _{Ic} | K _c |
| 4340 | 1.50 | 1.55 | 8 | 98 | 100 |
| | 1.50 | 1.50 | 7 | 99 | 99 |
| 9Ni-4Co | 1.50 | 2.0 | 18 | * | 109 |
| | 1.50 | 2.0 | 10 | * | 109 |
| AM 355 | 1.50 | 2.25 | 13 | 71 | 129 |
| | 1.50 | 1.69 | 7 | 55 | 79 |
| Maraging 250 | 1.50 | 1.86 | 15 | * | 107 |
| | 1.50 | 1.97 | 14 | 86 | 113 |
| INCO 718 | 1.50 | 1.89 | 25 | * | 341** |
| | 1.50 | 1.99 | 27 | * | 404** |
| T1 6Al-4V | 1.50 | 2.60 | 18 | * | 105 |
| T1 6Al-6V-2Sn | 1.50 | 1.75 | 20 | 54 | 90 |
| | 1.50 | 1.79 | 17 | 60 | 91 |
| PH 13-8 Mo | 1.50 | 1.60 | 5 | 98 | 107 |
| | 1.50 | 1.65 | 3 | 79 | 87 |

*No pop-in detected.

**Ratio of σ_N/σ_{ys} exceeded 0.8

II, C, Plane Stress (K_c) Crack Toughness Measurement (cont.)

when the stress-intensity factor of the stress field surrounding the crack reaches the value of K_c . The data show that with as little as 10 to 15% slant fracture, slow crack growth can still occur after the plane-strain pop-in, requiring a continuous increase in the applied stress to drive the crack, with the eventual unstable fracturing controlled by the K_c value.

1. The Leak-Before-Burst Fracture Toughness Criterion

For a crack length $2a$ in a large sheet, the K_c value permits an estimation of the critical crack for unstable crack propagation through the relationship

$$K_c^2 = \pi \sigma^2 a_1 \quad (\text{Eq 1})$$

where a_1 is the "effective" half-length of the crack. When the effective half-crack length is expressed in terms of the plastic-zone correction and the actual half-crack length, the effective half-crack length becomes

$$a_1 = a + K_c^2 / 2 \pi \sigma_{ys}^2 \quad (\text{Eq 2})$$

Substituting in Equation 1 and solving for K_c in terms of the actual half-length a ,

$$K_c^2 = \pi \sigma^2 a / [1 - 1/2 (\sigma/\sigma_{ys})^2] \quad (\text{Eq 3})$$

When the working stresses approach the yield strength, $\sigma = \sigma_{ys}$, Equation 3 becomes

$$K_c^2 / \pi \sigma_{ys}^2 = 2a \quad (\text{Eq 4})$$

The fracture-toughness criterion suggested by Irwin is, in effect, that if the quantity

$$K_c^2 / \pi \sigma_{ys}^2$$

exceeds twice the wall thickness, a small surface crack is unlikely to develop to the stage of unstable fracturing under stresses which do not exceed the yield strength. This quantity is the critical crack length at the yield strength for a through-the-thickness crack, so the criterion suggested is that the critical crack length for the material should exceed twice the wall thickness.

II, C, Plane Stress (K_c) Crack Toughness Measurement (cont.)

The usefulness of the leak-before-burst concept has received a large amount of study and trial in connection with steel rocket motor cases*.

2. Precrack Charpy Impact for Approximating K_c

In Appendix D of Volume I of AFMI-TR-68-163, the merits and limitations of the precrack Charpy impact test are discussed. The chief objection to the precrack Charpy test has come from those who have considered the test only in terms of a quantitative measure of fracture toughness. It has been suggested** that the basic limitation in the precracked Charpy test is the small size of the test specimen. In Appendix D of Volume I, it is shown that the small size of the test precrack Charpy specimen has not been a serious limitation and, in fact, can be its chief advantage. Moreover, because of the small specimen size and the inherent simplicity of impact testing, the Charpy test is easily and inexpensively conducted over a wide range of temperatures. Charpy test results have shown the importance of testing over a range of temperatures, particularly in K_c determinations where testing at a single temperature, as is often done when using much more expensive test methods, can be seriously misleading. Two points should be made clear with regard to the use of the precrack Charpy test; viz, (1) the principal advantage of the precrack Charpy is in its use as a screening test where an approximate fracture toughness value is desired; and (2) the precrack Charpy impact test provides a good approximation of K_c through the relationship

$$K_c^2 = E(W/A)$$

where the K_c instability is associated with a running crack under plane-stress conditions.

Examples of the correlation of precrack Charpy impact data and center-notch tensile data were presented in Appendix D of Volume I, together with a discussion of certain metallurgical complications in correlation studies. Correlation between the tests was obtained when the Charpy specimens were machined from the broken halves of the larger test specimen and, thus, the test material had identically the same heat-treatment history and notch orientation. Over the last several years a limited number of precrack Charpy tests have been made from prematurely burst Minuteman chambers. However, the data were not always taken from the immediate vicinity of the fracture origin, nor were the test specimens oriented to propagate fracture in the chamber-axial direction. In the following Phase II study, the Charpy specimens were oriented to propagate fracture in the chamber-axial direction and were machined from various locations, including a position as close to the fracture origin as possible.

*Irwin, G. R., Applied Materials Research, Vol. 3, pp 65, April 1964; Irwin, G. R. and Sullivan, A. M., Proc. Roy. Soc., A285, pp 141(1965); Gerberich, W. W., Metals Engr. Quarterly, Vol. 4(4), pp 23, November 1964 and Application of Fracture Toughness Parameters to Structural Metals, AIME Met. Soc. Conf., Vol. 31(1966) pp 86.

**Brown and Srawley, Plane-Strain Crack Toughness Testing, ASTM STP 410, pp 33.

SECTION III

DATA COMPILATION

The precrack Charpy impact data compiled from 69 forgings as contained in 14 second-stage Minuteman 6Al-4V titanium rocket motor cases are tabulated. The data from the individual tests are presented in Appendix I, together with summary tabulations of the form shown in Table IV. From Table IV, it will be seen that the data are presented as a function of: (1) test location within the chamber (forging-to-forging differences), (2) test location within a given forging (effect of thickness and end-to-end homogeneity), and (3) test temperature (at 120°F increments encompassing the range anticipated in service). The data obtained over a range of temperature were plotted as shown in Figure 6; these plots are presented in Appendix II.

TABLE IV

SUMMARY OF PRECRACK CHARPY IMPACT DATA FROM 6AL-4V TITANIUM CHAMBER 673122

| Minuteman Chamber SN | Component | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|-------------------------|-------------|--------------------------|-------------------|--------------------------|--------------------------|-----------------------------|
| | | | | -40 | RT | 200 |
| 673122 | Fwd Closure | 2-in. fwd of G1 weld | 0.102 | | 532 - 631 Avg (3) 573 | |
| | | G1 reinforced section | 0.177 | 280 - 452 Avg (3) 375 | 656 - 693 Avg (3) 679 | 753 - 1100 Avg (3) 964 |
| | | | | | | 1250 - 1340 Avg (3) 1293 |
| | | | | | | |
| | Fwd Cyl | G1 reinforced section | 0.171 | | 334 - 578 Avg (3) 439 | |
| | | 2-in. aft of G1 weld | 0.102 | | 396 - 412 Avg (3) 406 | |
| | | 2-in. fwd of G2 weld | 0.106 | | 498 - 588 Avg (3) 549 | |
| | | G2 reinforced section | 0.170 | 352 - 359 Avg (3) 355 | 408 - 554 Avg (3) 484 | 289 - 875 Avg (3) 638 |
| | Aft Cyl | G2 reinforced section | 0.171 | 378 - 464 Avg (3) 409 | 593 - 634 Avg (3) 619 | 1080 - 1330 Avg (3) 1167 |
| | | 2-in. aft of G2 weld | 0.097 | | 550 - 620 Avg (3) 585 | 719 - 865 Avg (3) 815 |
| | | 2-in. fwd of G3 weld | 0.094 | | 441 - 548 Avg (3) 484 | 1130 - 1300 Avg (3) 1200 |
| | | G3 reinforced section | 0.170 | | 387 - 631 Avg (3) 507 | |
| | Aft Closure | G3 reinforced section | 0.179 | 169 - 468 Avg (3) 329 | 601 - 640 Avg (3) 624 | 77J - 1060 Avg (3) 874 |
| | | 2-in. aft of G3 weld | 0.106 | | 487 - 519 Avg (3) 503 | 1140 - 1200 Avg (3) 1163 |

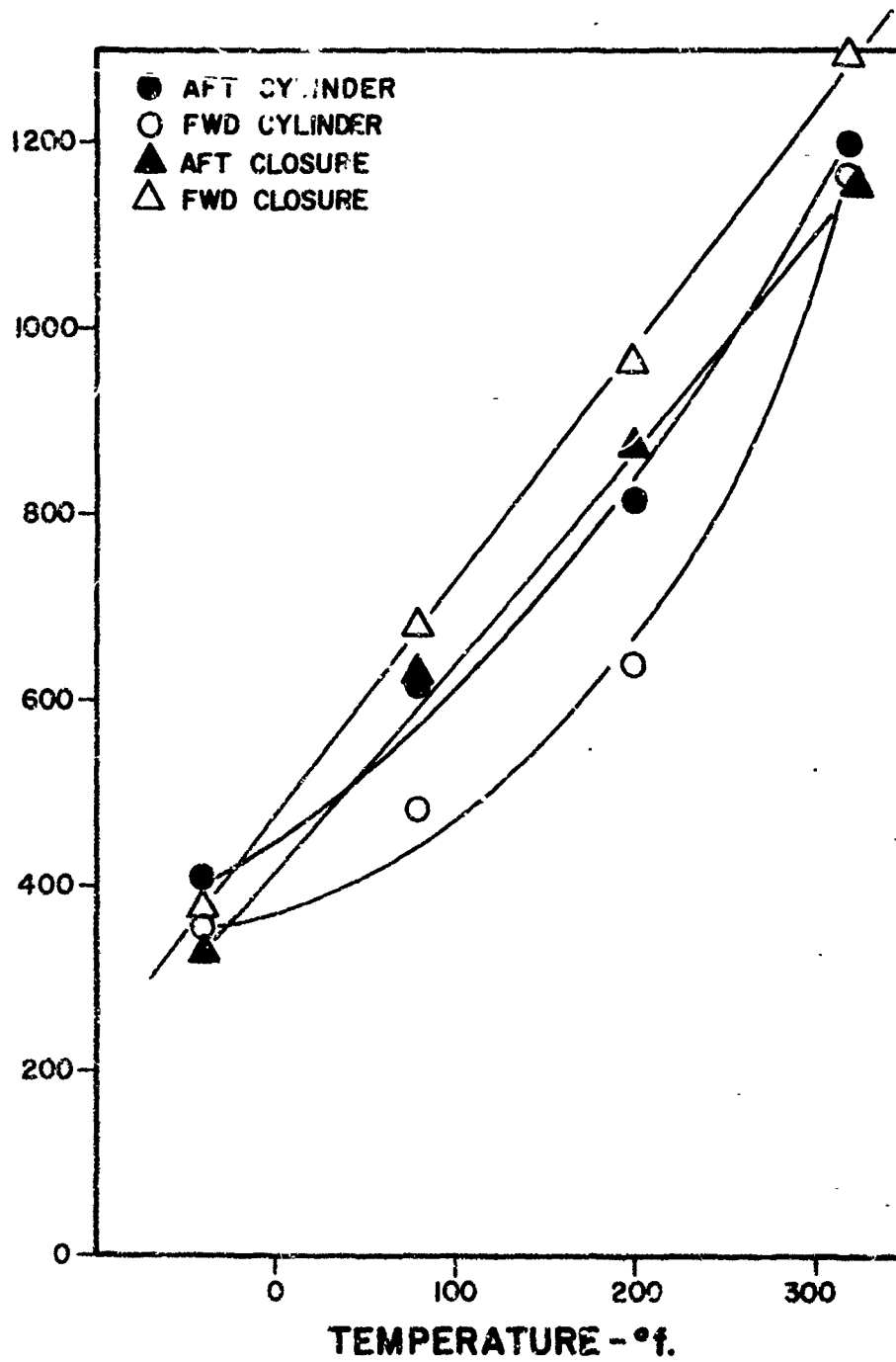


Figure 6. Effect of Test Temperature on the Precrack Charpy Impact W/A Values in 6Al-4V Titanium Chamber 673122

SECTION IV

DISCUSSION OF RESULTS

A. TEST REPRODUCIBILITY

Twenty-four tests were run from a single closure forging, with 12 specimens taken from the closure flange (0.110 in. thick) and 12 from the dome (0.070 in. thick). The fatigue crack depths for both sets ranged from approximately 0.05 to 0.10 in., with an average depth (24 specimens) of 0.072 in. From Figure 7, it will be seen that the variation in fatigue-crack depth had no discernible effect on the W/A value.

Each set of data was statistically tested. With the W/A values from the 12 dome specimens as input to the computer and a typical class interval of 440-540, the computer printout was as shown in Table V. Likewise, with the W/A values from 12 flange specimens as input to the computer and a typical class interval of 405-485, the computer printout was as shown in Table VI.

From a simple analysis of covariance, it was determined that there was a highly significant difference between the means of the flange and dome sections (significance level 0.0019). It is reasonable to assume that the highly significant difference between the means of the flange and dome is due to the difference in thickness and/or possible anisotropy due to a difference in specimen orientation. Multiple linear regression and correlation analysis was then employed to determine if crack depth had an effect on the two sets of 12 tests. The analysis showed that there was no correlation between the W/A value and net section within the limits investigated.

Table VII presents data on variability in the precrack Charpy impact W/A value as measured in Minuteman 6Al-4V titanium. The data presented in Table VII are for the body cylinders in each chamber without regard for possible differences between forgings or possible differences from end-to-end in a given forging. The variability is intended for use as a yardstick against which the seeming difference between averages is assessed. In this report, the following measures of variability are used: the variance, the standard deviation and the range of a sample. Table VII presents the sample variance (s^2), the sample standard deviation (s) and the sample mean. Note that the standard deviations for the individual chambers ranged from 54 to 174 in.-lb/in.², and when the data from all 26 forgings were tested for variability, the standard deviations were very large.

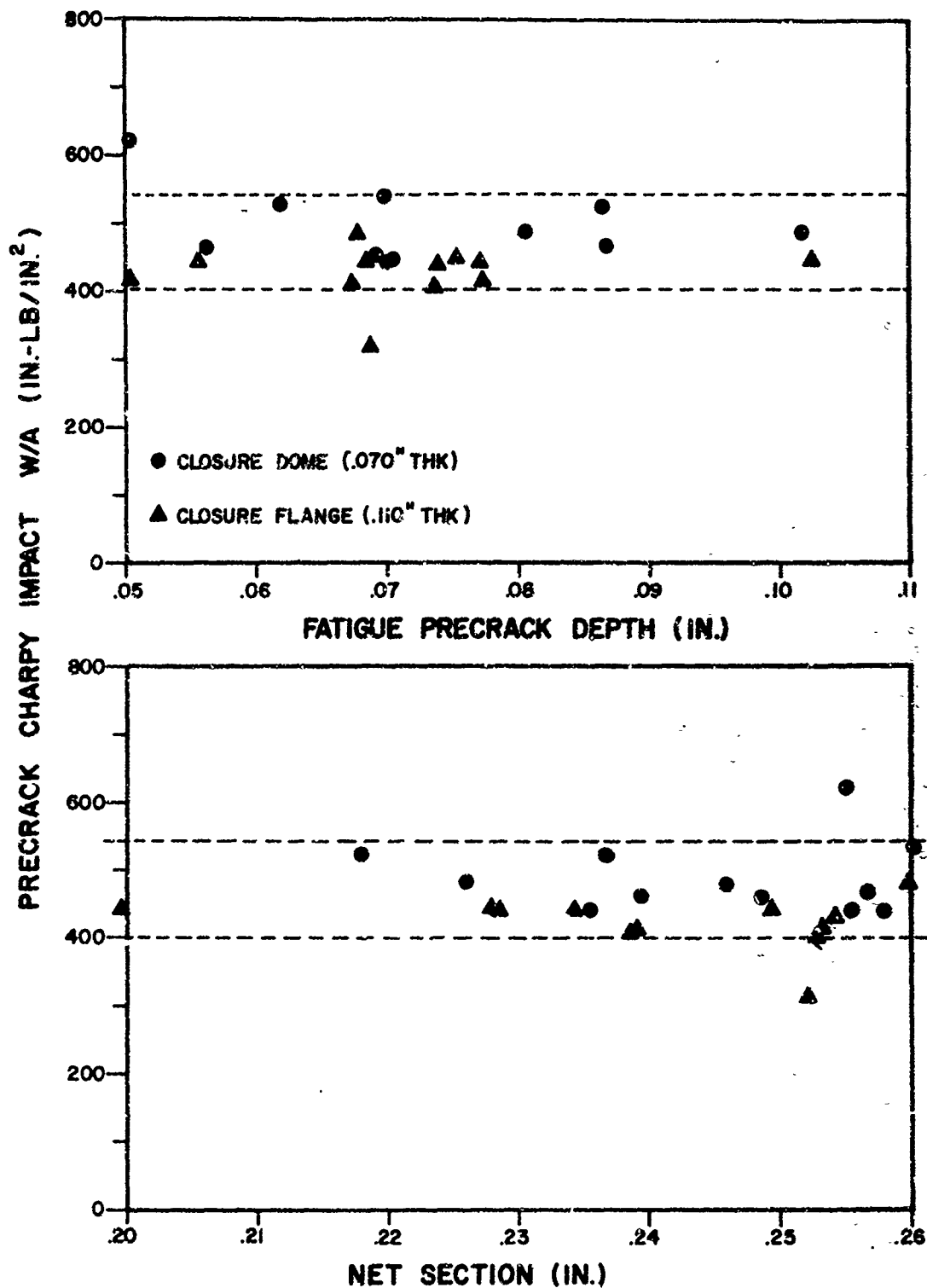


Figure 7. Effect of Crack Depth (Net Section) on Precrack Charpy W/A Values

TABLE V

COMPUTER PRINTOUT FOR REPLICATE TESTS OF CHAMBER R26 DOME MATERIAL.

DATA 472,486,463,540,483,456,448,443,465,524,526,623

SUMMARY STATISTICS

NUMBER OF VARIATES = 12
 ARITHMETIC MEAN = 494.083
 STANDARD DEVIATION = 49.4241
 VARIANCE = 2442.74
 COEFF OF VAR (PCT) = 10.003
 STANDARD SKEWNESS = 1.342
 STANDARD EXCESS = 1.159

ORDER STATISTICS

SMALLEST VARIATE = 443
 LOWER DECILE = 444.5
 FIRST QUARTILE = 457.75
 MEDIAN = 477.5
 THIRD QUARTILE = 525.5
 UPPER DECILE = 598.1
 LARGEST VARIATE = 623

 TOTAL RANGE = 180
 DECILE RANGE = 153.6
 SEMI-QUARTILE RANGE = 33.875
 BOWLEY'S SKEWNESS = .417
 PEARSON SKEWNESS = 1.007

FREQUENCY DISTRIBUTION

| FROM | UP TO BUT NOT INCLUDING | FREQUENCY | PERCENT FREQUENCY |
|------|----------------------------|-----------|----------------------|
| 440 | 540 | 10 | 83.333 |
| 540 | 640 | 2 | 16.667 |

CUMULATIVE DISTRIBUTION

| VALUE | NUMBER LESS THAN VALUE | PERCENT LESS THAN VALUE | VARIATE SUM - PCT LESS THAN VALUE |
|-------|---------------------------|----------------------------|--------------------------------------|
| 540 | 10 | 83.333 | 80.385 |
| 640 | 12 | 100. | 100. |

ORDERED ARRAY

| | | | |
|-----|-----|-----|-----|
| 443 | 463 | 483 | 526 |
| 448 | 465 | 486 | 540 |
| 456 | 472 | 524 | 623 |

TABLE VI

COMPUTER PRINTOUT FOR REPLICATE TESTS OF CHAMBER R26 FLANGE MATERIAL
DATA 419,410,484,446,415,443,449,437,443,318,445,407

S U M M A R Y S T A T I S T I C S

NUMBER OF VARIATES = 12
ARITHMETIC MEAN = 426.333
STANDARD DEVIATION = 38.5170
VARIANCE = 1483.56
COEFF OF VAR (PCT) = 9.034
STANDARD SKEWNESS = -1.541
STANDARD EXCESS = 2.669

O R D E R S T A T I S T I C S

SMALLEST VARIATE = 318
LOWER DECILE = 344.7
FIRST QUARTILE = 411.25
MEDIAN = 440
THIRD QUARTILE = 445.75
UPPER DECILE = 473.5
LARGEST VARIATE = 484

TOTAL RANGE = 166
DECILE RANGE = 128.8
SEMI-QUARTILE RANGE = 17.25
BOWLEY'S SKEWNESS = -.667
PEARSON SKEWNESS = -1.064

F R E Q U E N C Y D I S T R I B U T I O N

| FROM | UP TO BUT NOT INCLUDING | FREQUENCY | PERCENT FREQUENCY |
|------|----------------------------|-----------|----------------------|
| 245 | 325 | 1 | 8.333 |
| 325 | 405 | 0 | 0 |
| 405 | 485 | 11 | 91.667 |

C U M U L A T I V E D I S T R I B U T I O N

| VALUE | NUMBER LESS THAN VALUE | PERCENT LESS THAN VALUE | VARIATE SUM - PCT LESS THAN VALUE |
|-------|---------------------------|----------------------------|--------------------------------------|
| 325 | 1 | 8.333 | 6.216 |
| 405 | 1 | 8.333 | 6.216 |
| 485 | 12 | 100. | 100. |

O R D E R E D A R R A Y

| | | | |
|-----|-----|-----|-----|
| 318 | 415 | 443 | 446 |
| 407 | 419 | 443 | 449 |
| 410 | 437 | 445 | 484 |

TABLE VII

VARIABILITY IN THE PRECRACK CHARPY IMPACT W/A VALUE IN MINUTEMAN 6A1-4V TITANIUM

| Chamber | $\Sigma (W/A)$ | $\frac{\Sigma (W/A)^2}{x \times 10^6}$ | $\frac{(\Sigma W/A)^2}{x \times 10^6}$ | $\frac{n-1}{n}$ | $\frac{(\Sigma W/A)^2}{n} \times 10^6$ | $\frac{[\Sigma (W/A)^2 - (\Sigma W/A)^2/n]}{SS \times 10^6}$ | $\frac{[SS/n-1]}{s^2 \times 10^5}$ | Std. Devia. s | Sample Mean in.-lb/in. ² |
|---------------------|----------------|--|--|-----------------|--|--|------------------------------------|---------------|-------------------------------------|
| 226 0.10 in. | 18173 | 10.8910 | 330.2580 | 32 | 10.0078 | 0.8832 | 0.0276 | 166 | 551 |
| R41 0.10 in. | 7927 | 4.4284 | 62.8373 | 15 | 4.1891 | 0.2390 | 0.0170 | 130 | 528 |
| 2191456 0.10 in. | 8589 | 5.1850 | 73.7709 | 15 | 4.9180 | 0.2670 | 0.0190 | 138 | 573 |
| BL26 0.10 in. | 6311 | 3.1010 | 39.8287 | 13 | 3.0637 | 0.0373 | 0.0031 | 56 | 485 |
| 0.18 in. | 6464 | 3.0481 | 41.7833 | 14 | 2.9845 | 0.0636 | 0.0048 | 69 | 462 |
| 2192109 0.10 in. | 4649 | 1.9273 | 21.6132 | 12 | 1.8011 | 0.1262 | 0.0114 | 107 | 387 |
| 0.18 in. | 2163 | 0.9503 | 4.6786 | 5 | 0.9357 | 0.0146 | 0.0036 | 60 | 541 |
| R369 0.10 in. | 11375 | 5.6535 | 129.3906 | 24 | 5.3913 | 0.2622 | 0.0114 | 107 | 474 |
| 0.18 in. | 5752 | 1.9990 | 33.0855 | 17 | 1.9462 | 0.0528 | 0.0033 | 58 | 338 |
| R490 0.10 in. | 9131 | 3.9460 | 83.3752 | 22 | 3.7897 | 0.1563 | 0.0074 | 86 | 415 |
| 0.18 in. | 6553 | 2.4350 | 42.9418 | 18 | 2.3856 | 0.0494 | 0.0029 | 54 | 364 |
| R512 0.10 in. | 13513 | 7.9465 | 182.6012 | 24 | 7.6083 | 0.3382 | 0.0147 | 121 | 563 |
| 0.18 in. | 7674 | 3.4390 | 58.8903 | 18 | 3.2716 | 0.1674 | 0.0098 | 99 | 426 |

TABLE VII (cont.)

| Chamber | $\sum (W/A)$ | $\frac{\sum (W/A)^2}{x \cdot 10^6}$ | $\frac{(\sum W/A)^2}{x \cdot 10^6}$ | $\frac{n-1}{n}$ | $\frac{(\sum W/A)^2}{n} \times 10^6$ | $\frac{[\sum (W/A)^2 - (\sum W/A)^2/n]}{SS \times 10^6}$ | $\frac{[SS/n-1]}{s^2 \times 10^6}$ | Std. Devia. s | Sample Mean in.-lb/in. ² |
|----------------|--------------|-------------------------------------|-------------------------------------|-----------------|--------------------------------------|--|------------------------------------|---------------------|---|
| R516 | | | | | | | | | |
| 0.10 in. | 11412 | 6.0482 | 130.2337 | 24 | 5.4264 | 0.6218 | 0.0270 | 164 | 476 |
| 0.18 in. | 7189 | 2.9541 | 51.6817 | 18 | 2.8712 | 0.0829 | 0.0048 | 69 | 399 |
| R543 | | | | | | | | | |
| 0.10 in. | 11939 | 6.6815 | 142.5397 | 23 | 6.1973 | 0.4842 | 0.0220 | 148 | 519 |
| 0.18 in. | 6774 | 2.6523 | 45.8871 | 18 | 2.5492 | 0.1031 | 0.0060 | 78 | 376 |
| 673078 | | | | | | | | | |
| 0.10 in. | 12966 | 8.1633 | 168.1172 | 21 | 8.0056 | 0.1577 | 0.0079 | 89 | 617 |
| 0.18 in. | 8779 | 4.7125 | 77.0708 | 17 | 4.5336 | 0.1789 | 0.0112 | 106 | 516 |
| 673095 | | | | | | | | | |
| 0.10 in. | 9490 | 5.0418 | 90.0601 | 19 | 4.7400 | 0.3018 | 0.0167 | 129 | 499 |
| 0.18 in. | 8766 | 4.5357 | 76.8428 | 18 | 4.2690 | 0.2667 | 0.0156 | 125 | 487 |
| 673122 | | | | | | | | | |
| 0.10 in. | 9304 | 4.8956 | 86.5644 | 18 | 4.8091 | 0.0865 | 0.0050 | 71 | 517 |
| 0.18 in. | 10056 | 5.8040 | 101.1231 | 18 | 5.6179 | 0.1861 | 0.0109 | 105 | 559 |
| 674514 | | | | | | | | | |
| 0.10 in. | 5989 | 2.4850 | 35.8681 | 15 | 2.3912 | 0.0938 | 0.0067 | 82 | 399 |
| 0.18 in. | 5540 | 2.7262 | 30.6916 | 13 | 2.3608 | 0.3654 | 0.0304 | 174 | 426 |
| Composite: | | | | | | | | | |
| All Chambers | | | | | | | | | |
| 0.10 in. | 140768 | 76.3941 | 19815.6298 | 278 | 71.2792 | 5.1149 | 0.0184 | 136 | 506 |
| 0.18 in. | 75710 | 35.2563 | 5732.0041 | 174 | 32.9425 | 2.3138 | 0.0133 | 115 | 435 |
| Both Thick. | 215478 | 111.6504 | 46430.7685 | 452 | 102.7229 | 8.9275 | 0.0197 | 140 | 477 |

IV, A, Test Reprducibility (cont.)

| <u>Composite (All Chambers)</u> | <u>W/A</u> | <u>Standard Deviation</u> |
|-------------------------------------|------------|---------------------------|
| 0.10-in. | 506 | ± 136 |
| 0.18-in. | 435 | ± 115 |
| Combined Thickness | 477 | ± 140 |

On the other hand, when standard deviations were determined for a single forging at two thickness levels (from Tables V and VI), the standard deviations were small

| <u>R26 Forward Closure</u> | <u>W/A</u> | <u>Standard Deviation</u> |
|--------------------------------|------------|---------------------------|
| 0.072-in. | 494 | ± 49 |
| 0.110-in. | 426 | ± 38 |

The large standard deviations as obtained with composite data suggest the possibility of a large forging-to-forging variability in the W/A value. In contrast, the plane-strain (K_{IC}) crack toughness as measured in 109 forgings was 39 ksi-in.^{1/2} with a standard deviation of only 1.6 ksi-in.^{1/2}

B. FORGING ANISOTROPY AND INHOMOGENEITY

1. Anisotropy

In Phase I of this contract, a comparison between axial- and hoop-direction fracture using the precrack Charpy impact test revealed marked anisotropy in some forgings (see Figure 25, page 52 of Volume I). Therefore, in Phase II, wherever secondary hoop fracture developed in a chamber, the material at the junction of the hoop and axial fractures was tested for anisotropy. As noted in Table II a large number of forgings also were examined for anisotropy where there was no hoop-direction fracture.

The fracture in chamber R490 originated in the center girth weld and propagated forward and aft in the chamber with a single secondary fracture starting in the membrane wall near the aft grith weld and doubled back at approximately 45 degrees toward the center girth weld. Precrack Charpy impact specimens were machined from the two body cylinders on either side of the center girth weld (not at the juncture of the axial and 45 degree fractures). From summary Table VIII, it will be seen that the crack toughness in both cylinders was higher in the hoop direction.

TABLE VIII

SUMMARY OF PRECRACK CHARPY IMPACT TESTS FOR ANISOTROPY IN 6Al-4V TITANIUM FORGINGS

| <u>S/N</u> | <u>Minuteman Chamber Component</u> | <u>Thickness, in.</u> | <u>W/A Values (in.-lb/in.) Crack Propagation Direction</u> | |
|------------|------------------------------------|-----------------------|--|--------------------------------|
| | | | <u>Axial</u> | <u>Hoop</u> |
| 490 | Fwd Cyl | 0.109 | 321 - 466 Avg(3) <u>410</u> | 654 - 703 Avg(3) <u>680</u> |
| | Aft Cyl | 0.110 | 379 - 388 Avg(3) <u>382</u> | 403 - 439 Avg(3) <u>426</u> |
| R512 | Fwd Cyl | 0.108 | 526 - 532 Avg(3) <u>529</u> | 388 - 468 Avg(3) <u>436</u> |
| | Aft Cyl | 0.109 | 386 - 443 Avg(3) <u>414</u> | 414 - 539 Avg(3) <u>467</u> |
| R516 | Fwd Cyl | 0.105 | 315 - 375 Avg(3) <u>349</u> | 393 - 501 Avg(3) <u>459</u> |
| | Aft Cyl | 0.106 | 384 - 482 Avg(3) <u>444</u> | 345 - 400 Avg(3) <u>374</u> |
| R543 | Fwd Cyl | 0.106 | 401 - 500 Avg(3) <u>447</u> | 361 - 507 Avg(3) <u>450</u> |
| | Aft Cyl | 0.105 | 336 - 351 Avg(3) <u>343</u> | 546 - 646 Avg(3) <u>602</u> |
| 673078 | Aft Flange* | 0.107 | 567 - 642 Avg(3) <u>614</u> | 492 - 539 Avg(3) <u>519</u> |
| | Aft Cyl | 0.105 | 519 - 608 Avg(6) <u>569</u> | 611 - 702 Avg(6) <u>652</u> |
| 673095 | Aft Cyl* | 0.102 | 334 - 401 Avg(4) <u>379</u> | 280 - 325 Avg(3) <u>301</u> |
| | Phase I | 0.100 | 406 - 522 Avg(3) <u>460</u> | 303 - 416 Avg(9) <u>348</u> |
| 674514 | Aft Cyl* | 0.098 | 295 - 324 Avg(3) <u>306</u> | 274 - 320 Avg(3) <u>304</u> |
| | Phase I | 0.099 | 343 - 396 Avg(6) <u>366</u> | 274 - 330 Avg(6) <u>308</u> |
| 2192109 | Fwd Cyl* | 0.105 | 242 - 276 Avg(3) <u>263</u> | 340 - 381 Avg(3) <u>365</u> |
| | Phase I | 0.103 | 308 - 454 Avg(6) <u>432</u> | 459 - 518 Avg(6) <u>489</u> |

*Specimens taken at junction of hoop and axial fracture.

IV, 2, Forging Anisotropy and Inhomogeneity (cont.)

The fracture in chamber R512 originated in the forward cylinder approximately 3-1/2 in. from the center girth weld and propagated forward and aft in the chamber with no secondary fracture. Precrack Charpy impact specimens were machined from the two body cylinders on either side of the center girth weld. From summary Table VIII it will be seen that the crack toughness in the hoop direction was lower in the forward cylinder, but higher in the aft cylinder as compared with the axial direction.

The fracture in chamber R516 originated in the aft-cylinder reinforced section of the center girth weld, and propagated forward and aft in the chamber, with a single secondary fracture starting in the membrane wall near the aft girth weld and doubling back at approximately 45 degrees toward the center girth weld. Precrack Charpy impact specimens were machined from the two body cylinders on either side of the center girth weld (not at the juncture of the axial and 45° fractures). From summary Table VIII it will be seen that the crack toughness in the aft cylinder containing the 45 degree fracture was lower in the hoop direction than in the axial direction; in the forward cylinder, the crack toughness was higher in the hoop direction than in the axial direction.

The fracture in chamber R543 originated in the aft cylinder, 18 in. forward of the aft girth weld, and propagated forward and aft in the chamber with no secondary fracture. Precrack Charpy impact specimens were machined from the two body cylinders at the ends closest to the forward and aft girth welds. From summary Table VIII, it will be seen that the crack toughness in the hoop direction was higher than that in the axial direction in both cylinders.

The fracture in chamber 673078 originated in the center girth weld and propagated forward and aft, terminating in the aft skirt and propagating through the entire diameter of the forward dome. After crossing the aft girth weld, a secondary hoop fracture developed in the aft flange. Precrack Charpy impact specimens were machined from the junction of the hoop and axial fractures. From summary Table VIII, it will be seen that the crack toughness in the hoop direction of the aft flange of chamber 673078 was appreciably lower than that in the axial direction. In the aft cylinder, on the other hand, the data obtained in Phase I showed greater resistance to propagation in the hoop direction than in the axial direction. Likewise, from Phase I of the contract, the forward cylinder had greater toughness in the hoop direction (629 in.-lb/in.²) than in the axial direction (528 in.-lb/in.²).

Rupture of room-temperature-hydroburst chamber 673095 extended longitudinally from the aft Y-joint to the forward girth weld where it split and continued through the forward Y-joint at two locations. Two hoop-direction rips occurred in the aft barrel. The first extended 270 degrees in a clockwise

IV, B, Forging Anisotropy and Inhomogeneity (cont.)

direction at the midpoint of the barrel section; the second extended 200 degrees in a counter-clockwise direction near the center girth weld.* Precrack Charpy impact specimens were machined from the junction of the hoop and axial fractures just aft of the center girth weld, and the test results compared with those obtained from Phase-I material cut from a different location. From the summary Table VIII, it will be seen that the crack toughness in the hoop direction of chamber 673095 was lower than that in the axial direction at the junction of the hoop and axial fractures and, moreover, the toughness was lower at the juncture than at the location tested in Phase I.

The rupture of room-temperature-hydroburst chamber 674514 extended longitudinally from the aft Y-joint, through the forward Y-joint and and through the forward dome. A hoop-direction rip occurred in the aft barrel and extended approximately 330 degrees.* Precrack Charpy impact specimens were machined from the junction of the hoop and axial fractures in the aft cylinder, and the test results compared with those obtained from Phase-I material cut from a different location. From summary Table VIII, it will be seen that the crack toughness at the juncture of the fracture paths was approximately equal and, moreover, the hoop-direction data obtained in Phase I and Phase II were identical for all practical purposes. The crack toughness in the axial direction in the material location tested in Phase I had higher toughness than at the junction of the hoop and axial fracture.

The rupture of chamber 2192109 (tested at 212°F) originated in the aft cylinder at a point, as determined by break wires and stress-wave analysis, approximately 72 in. aft of the forward skirt. A hoop-direction rip occurred in the forward cylinder approximately 12 in. aft of the forward girth weld. Precrack Charpy impact specimens were machined from the forward cylinder at the junction of the hoop and axial fractures, and the test results compared with those obtained from Phase-I material cut from a different location. From summary Table VIII, it will be seen that the crack toughness in the axial direction, as tested at room temperature, was lower than that in the hoop direction and, therefore, did not explain the hoop-direction rip. However, the hoop direction data obtained at the juncture of the fractures was appreciably lower than those obtained from Phase-I material cut from a different location. Moreover, data were not obtained at the 212°F hydroburst test temperature and, therefore, it is possible that at 212°F the crack toughness in the hoop direction may have been lower than that in the axial direction.

2. Forging Inhomogeneity

Table IX summarizes the body-cylinder data that were taken to determine the variation in toughness from end-to-end in any given cylinder

*R. H. Powell, "Burst Test of High-Strength Minuteman Wing II, Second-Stage Motor Cases", Report No. 999M-FR-1 and 2, 18 September 1963; and Report No. 999M-R, 23 October 1963.

TABLE IX

SUMMARY OF PRECRACK CHARPY IMPACT TESTS FOR INHOMOGENEITY IN 6Al-4V TITANIUM FORGINGS

| Minuteman Chamber | | Reinforced Section* | | Membrane Section* | |
|----------------------|-----------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| S/N | Component | Fwd | Aft | Fwd | Aft |
| R369 52-in. Dia | Fwd Cyl | 286 - 303 Avg(3) <u>295</u> | 207 - 216 Avg(2) <u>211</u> | 316 - 330 Avg(3) <u>324</u> | 332 - 349 Avg(3) <u>342</u> |
| | Aft Cyl | 359 - 385 Avg(3) <u>374</u> | 350 - 377 Avg(3) <u>368</u> | 432 - 489 Avg(3) <u>455</u> | 472 - 514 Avg(3) <u>490</u> |
| R490 52-in. Dia | Fwd Cyl | 346 - 421 Avg(3) <u>378</u> | 323 - 366 Avg(3) <u>347</u> | 343 - 435 Avg(3) <u>393</u> | 321 - 466 Avg(3) <u>410</u> |
| | Aft Cyl | 315 - 380 Avg(3) <u>343</u> | 260 - 303 Avg(3) <u>289</u> | 379 - 388 Avg(3) <u>382</u> | 256 - 311 Avg(3) <u>284</u> |
| R512 52-in. Dia | Fwd Cyl | 362 - 456 Avg(3) <u>420</u> | 340 - 409 Avg(3) <u>368</u> | 468 - 540 Avg(3) <u>509</u> | 526 - 532 Avg(3) <u>529</u> |
| | Aft Cyl | 316 - 341 Avg(3) <u>326</u> | 368 - 372 Avg(3) <u>370</u> | 386 - 443 Avg(3) <u>414</u> | 405 - 436 Avg(3) <u>424</u> |
| R516 52-in. Dia | Fwd Cyl | 373 - 644 Avg(3) <u>465</u> | 328 - 405 Avg(3) <u>358</u> | 404 - 428 Avg(3) <u>415</u> | 315 - 375 Avg(3) <u>349</u> |
| | Aft Cyl | 389 - 457 Avg(3) <u>429</u> | 338 - 381 Avg(3) <u>362</u> | 384 - 482 Avg(3) <u>444</u> | 426 - 493 Avg(3) <u>469</u> |
| R543 52-in. Dia | Fwd Cyl | 394 - 436 Avg(3) <u>419</u> | 289 - 393 Avg(3) <u>352</u> | 401 - 500 Avg(3) <u>447</u> | 351 - 496 Avg(3) <u>445</u> |
| | Aft Cyl | 247 - 302 Avg(3) <u>280</u> | 269 - 361 Avg(3) <u>303</u> | 360 - 371 Avg(2) <u>366</u> | 336 - 351 Avg(3) <u>343</u> |
| 673078 44-in. Dia | Fwd Cyl | 530 - 564 Avg(3) <u>543</u> | 442 - 738 Avg(3) <u>617</u> | 518 - 701 Avg(3) <u>630</u> | 655 - 824 Avg(3) <u>727</u> |
| | Aft Cyl | 422 - 482 Avg(3) <u>456</u> | 462 - 512 Avg(3) <u>484</u> | 445 - 494 Avg(3) <u>476</u> | 555 - 643 Avg(3) <u>608</u> |
| 673095 44-in. Dia | Fwd Cyl | 543 - 674 Avg(3) <u>603</u> | 541 - 696 Avg(3) <u>634</u> | 608 - 783 Avg(3) <u>684</u> | 452 - 677 Avg(3) <u>598</u> |
| | Aft Cyl | 352 - 444 Avg(3) <u>386</u> | 352 - 392 Avg(3) <u>375</u> | 334 - 401 Avg(4) <u>379</u> | 355 - 419 Avg(3) <u>389</u> |
| 673122 44-in. Dia | Fwd Cyl | 334 - 578 Avg(3) <u>439</u> | 408 - 554 Avg(3) <u>484</u> | 396 - 412 Avg(3) <u>406</u> | 498 - 588 Avg(3) <u>549</u> |
| | Aft Cyl | 593 - 634 Avg(3) <u>619</u> | 387 - 631 Avg(3) <u>507</u> | 550 - 620 Avg(3) <u>585</u> | 441 - 548 Avg(3) <u>484</u> |

*Reinforced section nominally 0.18-in. thick and membrane wall nominally 0.10-in. thick, tested in their respective thicknesses.

IV, B, Forging Anisotropy and Homogeneity (cont.)

forging. Note that in a given section, there was sometimes a marked difference from end-to-end of a cylinder. For example, in chamber R359, in the reinforced section of the forward cylinder:

| <u>Aft</u> | <u>Forward</u> |
|-------------------|-------------------|
| 207 to 216 | 286 to 303 |
| Av (2) <u>211</u> | Av (3) <u>295</u> |

Note that the higher value obtained from the two tests at the aft end of the chamber (216 in.-lb/in.²) was appreciably lower than the lowest value obtained from the forward end of the cylinder (286 in.-lb/in.²); thus, from an engineering viewpoint, there was a significant difference between the arithmetic mean values (211 for the aft end and 295 for the forward end of the cylinder). Differences in toughness from end-to-end of a given cylinder could be the result of a difference in the forging working-temperature and/or thickness effects.

With regard to thickness, it should be noted that differences between the two thicknesses of Charpy specimens tested may be the result of one or a combination of three factors; viz, (1) a difference in lateral restraint in the test specimen per se due to thickness (width of test specimen); (2) a gradient of microstructure in the chamber wall due to the limitations of 6Al-4V titanium hardenability (cylinders were solution treated with a 1/2-in. wall and then machined to the nominal 0.10-in. wall); and (3) a difference in interstitial content due to a gradient of chemistry in the thickness direction (surfaces of the 1/2-in.-thick cylinders were badly contaminated as the result of solution treating in air; out-of-roundness after water quenching can result in local sections of higher-than-average interstitial content in the finish-machined part). Thus, any one or a combination of the above factors could have caused a variable "thickness" effect from cylinder to cylinder. Consider, for example, a comparison between the W/A values obtained from the two sections at the aft end of the aft cylinder of chamber R369:

| <u>Reinforced</u> | <u>Membrane</u> |
|-------------------|-------------------|
| 350 to 377 | 472 to 514 |
| Av (3) <u>368</u> | Av (3) <u>490</u> |

Note that the highest value obtained from the three tests of the reinforced section (377 in.-lb/in.²) was appreciably lower than the lowest value obtained from the three tests of the membrane wall (472 in.-lb/in.²); thus, from an engineering viewpoint, there was a significant difference between the arithmetical mean values (368 for the thicker wall and 490 in.-lb/in.² for the membrane wall). This trend is consistent with the effect of thickness usually observed in plane-stress fracture testing. From an examination of Table IX, it will be seen that

IV, B, Forging Anisotropy and Inhomogeneity (cont.)

the scatter bands obtained in the two thicknesses sometimes overlapped and, therefore, there was uncertainty from an engineering viewpoint as to whether the difference in arithmetical mean between the two thicknesses tested was significant; this question will be reconsidered in subsequent paragraphs dealing with a statistical evaluation of the data. However, it should be noted from Table IX when there was no overlap of the W/A values, as illustrated above for chamber R369, the data always showed the reinforced section to have the lower toughness.

Figure 8 presents, in bar graph form, the data of Table IX. A comparison of adjacent bars (solid versus stippled) shows the difference between reinforced and membrane walls, and a comparison of adjacent pairs of bars shows the variation, if any, from end-to-end of any given forging. The top of any given bar represents the highest W/A values measured, and the top of the solid (or stippled) part of any given bar represents the lowest value measured; the solid point is the arithmetical mean of the W/A values for any given bar. Note that with few exceptions, the reinforced (thicker) sections had lower arithmetical mean values than the membrane sections. The exceptions generally involved differences of less than 50 in.-lb/in.² Figure 8 also shows the marked differences in toughness that existed from forging to forging in a given chamber. Note, for example, the difference between the forward and aft cylinders in chamber R369. Other chambers, for example 673095, had even greater differences in toughness from forging to forging.

An analysis of variance was made to determine if there was a statistically significant difference (1) between cylinders, (2) between ends of cylinders, and (3) between thicknesses in a given cylinder. On the basis of an analysis of variance of the data from the body cylinders of eight chambers, it was determined that (1) there was a highly significant difference between cylinders (significance level 0.0001), and (2) there was a highly significant difference between the reinforced sections and the membrane walls (significance level 0.0002), but there appeared to be no significant difference between ends of cylinders (significance level 0.3120).

When the data were divided into two sets, one for membrane-wall and one for reinforced-section samples, the analysis of variance showed for the reinforced-section samples a highly significant difference between cylinders (significance level 0.0004), but, again, there appeared to be no significant difference between ends of cylinders (significance level 0.1384). For the membrane-wall samples, there was a highly significant difference between cylinders (significance level 0.0004) and a highly significant difference between ends of cylinders (significance level 0.0021).

C. EFFECT OF CHEMISTRY AND FORGING PRACTICE

The precrack Charpy impact W/A values tabulated in Appendix A were analyzed statistically to determine the effect of interstitials (C, N₂, H₂,

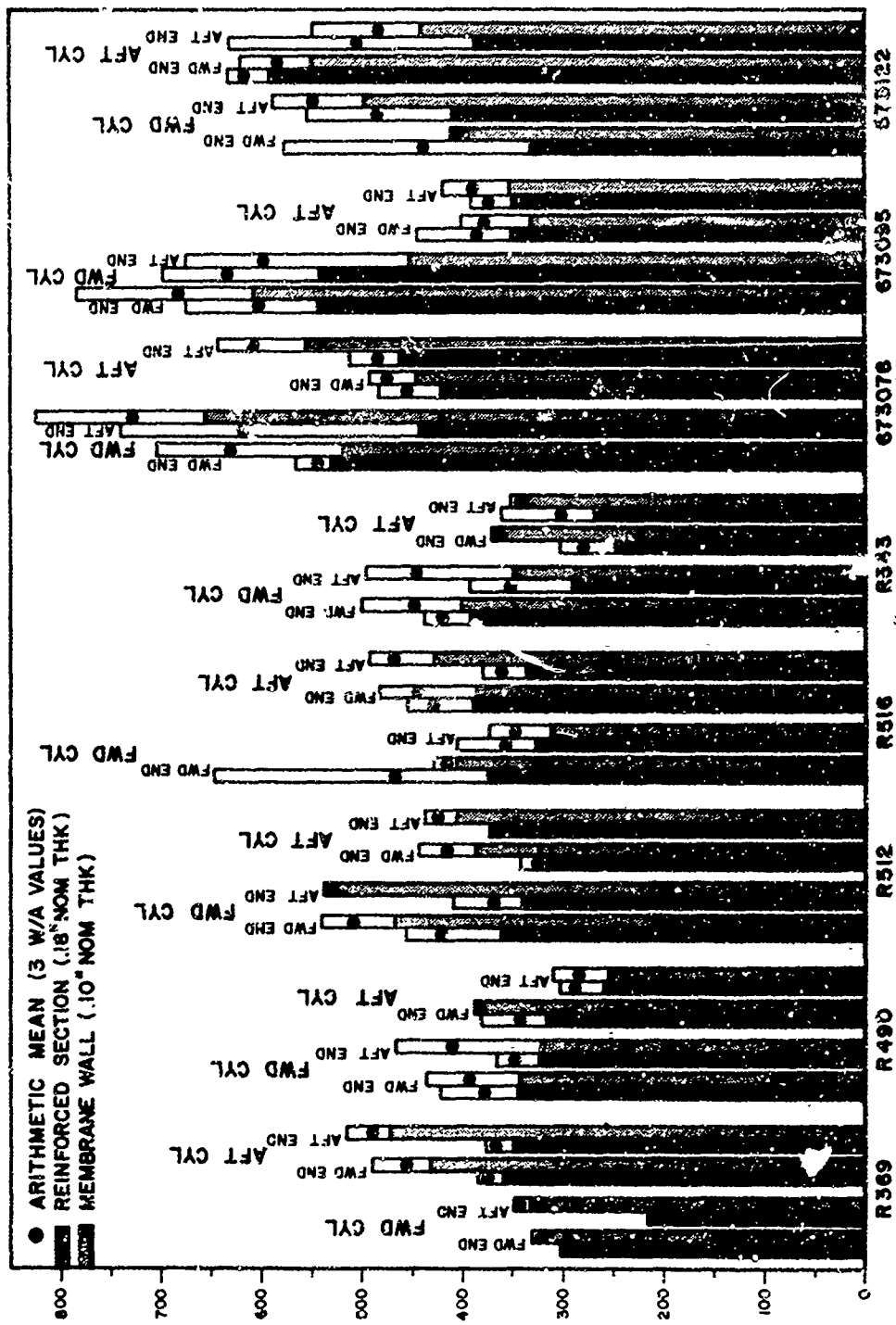


Figure 8. Inhomogeneity and Thickness Effects in 6Al-4V Titanium Forgings

IV, C, Effect of Chemistry and Forging Practice (cont.)

and O_2) on W/A values. It must be pointed out that the statistical results are valid only for materials having the chemistry of 6Al-4V titanium comparable to that of these data. The data were separated according to whether they were taken from the membrane wall or reinforced section; i.e., one set was for a nominal 0.10-in. thickness and the other set for a nominal 0.18-in. thickness.

From Table X, it is obvious that there are basically three types of forgings and several aging temperatures involved in the data collection. Before the W/A values could be tested for dependence on chemistry, it was necessary to determine the effect of the type of forging and/or aging temperature on the W/A values.

1. Membrane 0.10-in.-Thick Material

When the data were separated into three categories, one for each type of forging, and analyzed by one-way multiple covariance analysis, it was found that there were significant differences in the means among forging types. The data were again separated, this time into two categories, one for those specimens aged at temperatures below or at 1000°F, and the other for those specimens aged above 1000°F. When the data were analyzed by analysis of variance, it was found that there was no difference between the means for the aging temperatures. Also, it was found that there were no forging-temperature interactions.

Since the W/A values were dependent on the type of forging, the data were separated into three categories, one for each type of forging. Multiple regression and correlation analyses were used to determine if the W/A values, for each forging type, were a function of carbon, oxygen, hydrogen, and/or nitrogen. The method of least squares was used to develop equations which gave the best fit to the data for each combination of interstitials. The hypothesis was made that the slope of each curve was zero and the "T" test was used to test the hypothesis. In Table XI, those instances where the hypothesis was false, i.e., where there was a dependence of W/A on chemistry, an asterisk is used to identify the elements that influence the W/A value. The results as presented in Table XI, may be summarized as follows: for closed-die forgings there is a correlation between W/A and O_2 , and for ring-rolled forgings and extrusions, the strongest correlation was between W/A and C. The reason for this may be contained in the range of interstitial elements found in each forging type, as shown in the following tabulations:

TABLE X

CHEMISTRY OF MINUTEMAN CHAMBER COMPONENTS

| Chamber/ Component | Type of Forging | Al | V | Fe | C | N ₂ | H ₂ | O ₂ | Solution Temp., °F | Aging Temp. °F |
|-----------------------|--------------------|------|------|-------|-------|----------------|----------------|----------------|-----------------------|----------------------|
| R26 | | | | | | | | | | |
| Fwd Clos | Closed Die | | | | | | | | 1780 | 1000 |
| Fwd Cyl | Ring Roll | | | | | | | | 1750 | 1000 |
| Aft Cyl | Ring Roll | | | | | | | | 1750 | 1000 |
| Aft Fla | - | | | | | | | | 1780 | 1000 |
| 2191456 | | | | | | | | | | |
| Fwd Clos | Closed Die | 6.12 | 4.02 | 0.30 | 0.03 | 0.014 | 0.008 | 0.20 | 1750 | 1100 |
| Fwd Cyl | Ring Roll | 6.22 | 4.15 | 0.18 | 0.04 | 0.007 | 0.006 | 0.17 | 1750 | 1050 |
| Aft Cyl | Ring Roll | 6.52 | 4.15 | 0.158 | 0.02 | - | 0.006 | 0.14 | 1750 | 1100 |
| Aft Fla | Closed Die | 6.40 | 4.08 | 0.17 | 0.01 | 0.024 | 0.0098 | 0.12 | 1750 | 1100 |
| BL26 | | | | | | | | | | |
| Fwd Clos | Closed Die | 6.38 | 4.18 | 0.18 | 0.08 | 0.028 | 0.0010 | 0.166 | 1050 | 1125 |
| Fwd Cyl | - | 6.18 | 4.33 | 0.19 | 0.05 | 0.039 | 0.0015 | 0.150 | 1750 | 1100 |
| Aft Cyl | - | 6.09 | 4.34 | 0.19 | 0.03 | 0.024 | 0.0022 | 0.183 | 1750 | 1000 |
| Aft Fla | Closed Die | 6.08 | 4.13 | 0.19 | 0.07 | 0.029 | 0.0041 | 0.168 | 1750 | 1125 |
| 673078 | | | | | | | | | | |
| Fwd Clos | Closed Die | 6.30 | 4.06 | 0.16 | 0.04 | 0.017 | 0.0024 | 0.184 | 1750 | 1000 |
| Fwd Cyl | Extrusion | 6.55 | 4.02 | 0.23 | 0.05 | 0.011 | 0.0023 | 0.174 | 1750 | 1000 |
| Aft Cyl | Extrusion | 6.35 | 4.08 | 0.21 | 0.02 | 0.016 | 0.0030 | 0.192 | 1750 | 1000 |
| Aft Fla | Closed Die | 6.40 | 4.16 | 0.13 | 0.003 | 0.016 | 0.0025 | 0.11 | 1750 | 1000 |
| 673095 | | | | | | | | | | |
| Fwd Clos | Closed Die | 6.35 | 4.16 | 0.14 | 0.06 | 0.013 | 0.0017 | 0.16 | 1775 | 1000 |
| Fwd Cyl | Ring Roll | 6.10 | 3.96 | 0.19 | 0.02 | 0.014 | 0.0033 | 0.19 | 1775 | 1000 |
| Aft Cyl | Ring Roll | 6.48 | 3.62 | 0.18 | 0.08 | 0.019 | 0.0034 | 0.22 | 1775 | 1000 |
| Aft Fla | Closed Die | 6.39 | 3.90 | 0.18 | 0.03 | 0.018 | 0.0027 | 0.19 | 1750 | 1000 |
| 673122 | | | | | | | | | | |
| Fwd Clos | Closed Die | 6.18 | 3.98 | 0.08 | 0.03 | 0.040 | 0.0036 | 0.162 | 1800 | 1000 |
| Fwd Cyl | Ring Roll | 6.26 | 4.13 | 0.08 | 0.05 | 0.031 | 0.0077 | 0.165 | 1800 | 950 |
| Aft Cyl | Ring Roll | 6.10 | 4.02 | 0.07 | 0.05 | 0.018 | 0.0055 | 0.171 | 1830 | 1000 |
| Aft Fla | Ring Roll | 6.38 | 4.13 | 0.08 | 0.04 | 0.026 | 0.0044 | 0.170 | 1810 | 900 |
| 674514 | | | | | | | | | | |
| Fwd Clos | Closed Die | 6.07 | 4.09 | 0.07 | 0.05 | 0.049 | 0.0003 | 0.134 | 1750 | 1000 |
| Fwd Cyl | Extrusion | 5.95 | 4.12 | 0.10 | 0.04 | 0.034 | 0.0031 | 0.162 | 1750 | 1000 |
| Aft Cyl | Extrusion | 6.00 | 4.18 | 0.10 | 0.03 | 0.031 | 0.0010 | 0.157 | 1750 | 1000 |
| Aft Fla | Ring Roll | 6.15 | 4.17 | 0.09 | 0.04 | 0.045 | 0.0082 | 0.148 | 1750 | 1000 |
| 2192109 | | | | | | | | | | |
| Fwd Clos | Closed Die | 6.42 | 4.33 | 0.24 | 0.023 | 0.017 | 0.0021 | 0.185 | 1750 | 1000 |
| Fwd Cyl | Extrusion | 6.31 | 4.41 | 0.15 | 0.021 | 0.011 | 0.0016 | 0.17 | 1750 | 1000 |
| Aft Cyl | Extrusion | 6.42 | 4.48 | 0.15 | 0.027 | 0.007 | 0.0015 | 0.19 | 1750 | 1000 |

TABLE X (cont.)

| Chamber/ Component | Type of Forging | Al | V | Fe | C | N ₂ | P ₂ | O ₂ | Solution Temp., °F | Aging Temp., °F |
|-----------------------|--------------------|------|------|-------|-------|----------------|----------------|----------------|-----------------------|--------------------|
| R369 | | | | | | | | | | |
| Fwd Skrt | Ring Roll | 6.50 | 3.90 | 0.13 | 0.025 | 0.032 | 0.0054 | 0.16 | 1800 | 1000 |
| Fwd Clos | Closed Die | 6.65 | 4.30 | 0.24 | 0.031 | 0.007 | 0.0019 | 0.15 | 1750 | 1050 |
| Fwd Cyl | Extrusion | 6.3 | 4.25 | 0.18 | 0.024 | 0.010 | 0.005 | 0.185 | 1775 | 1075 |
| Aft Cyl | Extrusion | 6.5 | 4.1 | 0.18 | 0.24 | 0.013 | 0.0075 | 0.17 | 1775 | 1075 |
| Aft Clos | Closed Die | 6.70 | 4.00 | 0.15 | 0.030 | 0.010 | 0.0047 | 0.19 | 1750 | 1000 |
| Aft Skrt | Ring Roll | 6.52 | 4.33 | 0.30 | 0.039 | 0.009 | 0.0051 | 0.17 | 1750 | 1050 |
| R490 | | | | | | | | | | |
| Fwd Skrt | Ring Roll | 6.53 | 4.10 | 0.16 | 0.013 | 0.011 | 0.0043 | 0.18 | 1750 | 1050 |
| Fwd Clos | Closed Die | 6.64 | 3.87 | 0.17 | 0.017 | 0.011 | 0.0019 | 0.17 | 1750 | 1000 |
| Fwd Cyl | Extrusion | 6.25 | 4.1 | 0.175 | 0.022 | 0.014 | 0.003 | 0.18 | 1750 | 1025 |
| Aft Cyl | Extrusion | 6.4 | 4.15 | 0.19 | 0.022 | 0.011 | 0.0035 | 0.18 | 1750 | 1025 |
| Aft Clos | Closed Die | 6.54 | 3.97 | 0.15 | 0.046 | 0.013 | 0.0021 | 0.16 | 1750 | 1000 |
| Aft Skrt | Ring Roll | 6.62 | 3.89 | 0.16 | 0.031 | 0.011 | 0.0021 | 0.14 | 1750 | 1000 |
| R512 | | | | | | | | | | |
| Fwd Skrt | Ring Roll | 6.64 | 3.95 | 0.13 | 0.021 | 0.008 | 0.0065 | 0.15 | 1750 | 1000 |
| Fwd Clos | Closed Die | 6.68 | 3.60 | 0.13 | 0.019 | 0.011 | 0.0033 | 0.14 | 1750 | 1000 |
| Fwd Cyl | Extrusion | 6.2 | 4.15 | 0.16 | 0.022 | 0.010 | 0.0065 | 0.185 | 1750 | 1025 |
| Aft Cyl | Extrusion | 6.1 | 4.05 | 0.155 | 0.024 | 0.010 | 0.0045 | 0.175 | 1750 | 1025 |
| Aft Clos | Closed Die | 6.50 | 4.01 | 0.20 | 0.018 | 0.013 | 0.0019 | 0.17 | 1750 | 1000 |
| Aft Skrt | Ring Roll | 6.58 | 3.99 | 0.16 | 0.017 | 0.013 | 0.0032 | 0.14 | 1750 | 1000 |
| R516 | | | | | | | | | | |
| Fwd Skrt | Ring Roll | 6.53 | 4.10 | 0.16 | 0.013 | 0.011 | 0.0043 | 0.18 | 1750 | 1050 |
| Fwd Clos | Closed Die | 6.57 | 4.00 | 0.20 | 0.019 | 0.009 | 0.0036 | 0.16 | 1750 | 1050 |
| Fwd Cyl | Extrusion | 6.55 | 4.15 | 0.21 | 0.024 | 0.012 | 0.0085 | 0.19 | 1750 | 1025 |
| Aft Cyl | Extrusion | 6.2 | 4.2 | 0.21 | 0.021 | 0.014 | 0.0085 | 0.185 | 1750 | 1025 |
| Aft Clos | Closed Die | 6.66 | 3.83 | 0.16 | 0.016 | 0.013 | 0.0020 | 0.19 | 1750 | 1050 |
| Aft Skrt | Ring Roll | 6.57 | 3.96 | 0.14 | 0.048 | 0.010 | 0.0031 | 0.13 | 1750 | 1100 |
| R543 | | | | | | | | | | |
| Fwd Skrt | Ring Roll | 6.24 | 4.01 | 0.15 | 0.020 | 0.013 | 0.0023 | 0.15 | 1780 | 1000 |
| Fwd Clos | Closed Die | 6.14 | 4.15 | 0.17 | 0.026 | 0.010 | 0.0016 | 0.13 | 1750 | 1100 |
| Fwd Cyl | Extrusion | 6.5 | 4.45 | 0.08 | 0.02 | 0.012 | 0.0058 | 0.174 | 1750 | 1025 |
| Aft Cyl | Extrusion | 6.3 | 4.25 | 0.19 | 0.024 | 0.012 | 0.007 | 0.195 | 1750 | 1025 |
| Aft Clos | Closed Die | 6.49 | 3.61 | 0.18 | 0.027 | 0.012 | 0.0044 | 0.12 | 1750 | 1050 |
| Aft Skrt | Ring Roll | 6.55 | 4.08 | 0.15 | 0.016 | 0.012 | 0.0049 | 0.14 | 1750 | 1050 |

TABLE XI

SUMMARY OF MULTIPLE REGRESSION AND CORRELATION ANALYSIS FOR MEMBRANE-WALL MATERIAL

| Interstitial Combinations Investigated | Closed-Die Forgings | | Ring-Rolled Forgings | | Extrusions | |
|--|----------------------------|---------------------------|----------------------------|-----------------------------|----------------------------|---------------------------|
| | Correlation Coefficient | Regression Coefficient | Correlation Coefficient | Regression Coefficient | Correlation Coefficient | Regression Coefficient |
| C, H_2 , O_2 | * | O_2 | * | C | * | C |
| C | - | - | * | C | * | C |
| N_2 | - | - | * | N_2 | - | - |
| H_2 | - | - | - | - | - | - |
| O_2 | * | O_2 | * | O_2 | - | - |
| (N_2+O_2) | * | (N_2+O_2) | * | (N_2+O_2) | - | - |
| (H_2+O_2) | * | (H_2+O_2) | * | (H_2+O_2) | - | - |
| C, N_2 | - | - | * | C, N_2 | * | C |
| C, H_2 | - | - | * | C, H_2 | * | C |
| C, C_2 | * | O_2 | * | C | * | C |
| N_2 , H_2 | - | - | * | N_2 | - | - |
| N_2 , O_2 | * | O_2 | * | N_2 , O_2 | - | - |
| H_2 , O_2 | * | O_2 | * | H_2 , O_2 | - | - |
| C, N_2 , H_2 | - | - | * | C | * | C |
| C, N_2 , O_2 | - | - | * | C, N_2 | * | C |
| C, H_2 , O_2 | * | O_2 | * | C | * | C |
| N_2 , H_2 , O_2 | * | O_2 | * | H_2 , O_2 | - | - |

* Significance Level 0.05

IV, C, Effect of Chemistry and Forging Practice (cont.)

FORGINGS TESTED IN MEMBRANE WALL

| | <u>No.</u> <u>Forgings</u> | <u>Carbon</u> | <u>Nitrogen</u> | <u>Hydrogen</u> | <u>Oxygen</u> |
|----------------------|-------------------------------|-------------------|-------------------|---------------------|-------------------|
| Closed-die Forgings | 19 | 0.010 to 0.050 | 0.009 to 0.024 | 0.0016 to 0.0047 | 0.110 to 0.200 |
| Ring-rolled Forgings | 18 | 0.013 to 0.050 | 0.008 to 0.032 | 0.0021 to 0.0065 | 0.130 to 0.190 |
| Extrusions | 16 | 0.020 to 0.030 | 0.007 to 0.016 | 0.0010 to 0.0075 | 0.157 to 0.195 |

Note that for the closed-die forgings there was a considerable spread, within the limits, in the amount of carbon and oxygen, and relatively little spread in the amount of nitrogen and hydrogen. For ring-rolled forgings, the spread in carbon is approximately the same as for the closed-die forgings, but there was a smaller spread in oxygen and a slight increase in spread for nitrogen and hydrogen as compared with the closed-die forgings. In the extrusions, the spread for all four interstitials was appreciably smaller than in either the closed-die or ring-rolled forgings. The statistical-analysis results in Table XI are generally consistent with the above observations. For closed-die forging, W/A was found to be dependent on oxygen, and there was no interaction with the other three elements. For ring-rolled forgings, W/A was dependent primarily on carbon and to a lesser degree on nitrogen and oxygen. For extrusions, W/A was solely dependent on carbon content. For the conditions investigated, the above results indicate that the W/A value may be more dependent on carbon, within prescribed limits, than on oxygen with the exception of those instances when oxygen varied widely.

On the basis of the available data, equations were developed whereby W/A was given as a function of interstitial content. The equations, determined by the computer program, were as follows:

Closed-die Forgings: $W/A = 658.0 - 914.0(C) + 677.7(N_2) + 737.4(H_2) - 928.8(O_2)$
 Ring-roll Forgings: $W/A = 869.6 - 3810.8(C) - 3057.1(N_2) - 784.5(H_2) - 622.3(O_2)$
 Extrusions: $W/A = 19.3 + 8072.6(C) - 2303.8(N_2) + 165.9(H_2) + 1360.2(O_2)$

Note that the equation for ring-rolled forgings was of the form that might be expected, where the toughness value decreases by the addition of interstitials.

2. Reinforced-Section Material

When the data were separated into three categories, one for each type of forging, and analyzed by one-way multiple covariance analysis, it was found that there was no significant difference in the means among forging types. The data were again separated, this time into two categories; one for

IV, C, Effect of Chemistry and Forging Practice (cont.)

those specimens aged at temperatures below or at 1000°F, and the other for those specimens aged above 1000°F. When the data were analyzed by analysis of variance, it was found that there was a difference in the means for the two temperature levels. However, it was found that there was no forging-temperature interaction. The range of interstitial elements found in each forging type is shown in the following tabulation:

FORGINGS TESTED IN THE REINFORCED SECTION

| | <u>No.</u> <u>Forgings</u> | <u>Carbon</u> | <u>Nitrogen</u> | <u>Hydrogen</u> | <u>Oxygen</u> |
|------------------------|-------------------------------|-------------------|-------------------|---------------------|-------------------|
| Closed-die Forgings | 19 | 0.010 to 0.046 | 0.007 to 0.024 | 0.0016 to 0.0047 | 0.110 to 0.190 |
| Ring-roll Forgings | 6 | 0.040 to 0.050 | 0.007 to 0.045 | 0.0044 to 0.0077 | 0.140 to 0.170 |
| Extrusions | 1 | 0.020 to 0.040 | 0.010 to 0.019 | 0.0010 to 0.0075 | 0.150 to 0.195 |

Since the W/A values were dependent on the aging temperature, the data were separated into two categories, one for each temperature range. Multiple regression and correlation analysis was used to determine if the W/A values, for each temperature range, were a function of carbon, oxygen, hydrogen, or nitrogen. The results of the multiple regression and correlation analysis are summarized in Table XII. The method of least squares was used to develop equations for each combination of interstitials which gave the best fit to the data. The hypothesis was made that the slope of each curve was zero and the "T" test was used to test the hypothesis. In Table XII, those instances where the hypothesis was false; i.e., where there was a dependence of W/A on chemistry, and asterisk was used to identify the elements that influence the W/A value. The data in Table XII show that for each aging temperature range, the W/A value was dependent on oxygen content.

On the basis of the available data, equations were developed whereby W/A was given as a function of interstitial content. The equations determined by the computer program were as follows:

For aging temperature $\leq 1000^{\circ}\text{F}$

$$\text{W/A} = 915.4 + 278.8(\text{C}) - 1207.2(\text{N}_2) + 9047.4(\text{H}_2) - 2614.6(\text{O}_2)$$

For aging temperature $> 1000^{\circ}\text{F}$

$$\text{W/A} = 716.5 - 3421.8(\text{C}) + 4905.6(\text{N}_2) - 178.0(\text{H}_2) - 1851.7(\text{O}_2)$$

The range of interstitial elements found in the forgings that fall into the two categories of aging temperature is shown in the following tabulation:

TABLE XII

SUMMARY OF MULTIPLE REGRESSION AND CORRELATION ANALYSIS
FOR REINFORCED-SECTION MATERIAL

| Interstitial Combinations Investigated | Aging Temperature (°F) | | | |
|---|----------------------------|-----------------------------------|----------------------------|-----------------------------------|
| | ≤ 1000 | | > 1000 | |
| | Correlation Coefficient | Regression Coefficient | Correlation Coefficient | Regression Coefficient |
| C, N ₂ , H ₂ , O ₂ | * | O ₂ | * | O ₂ |
| C | - | - | - | - |
| N ₂ | - | - | - | - |
| H ₂ | - | - | - | - |
| O ₂ | * | O ₂ | * | O ₂ |
| (N ₂ +O ₂) | * | (N ₂ +O ₂) | * | (N ₂ +O ₂) |
| (H ₂ +O ₂) | * | (H ₂ +O ₂) | * | (H ₂ +O ₂) |
| C, N ₂ | - | - | - | - |
| C, H ₂ | - | - | - | - |
| C, O ₂ | * | O ₂ | * | C, O ₂ |
| N ₂ , H ₂ | - | - | - | - |
| N ₂ , O ₂ | - | - | * | O ₂ |
| H ₂ , O ₂ | * | O ₂ | * | O ₂ |
| C, N ₂ , H ₂ | - | - | - | - |
| C, N ₂ , O ₂ | * | O ₂ | * | O ₂ |
| C, H ₂ , O ₂ | * | O ₂ | * | C, O ₂ |
| N ₂ , H ₂ , O ₂ | * | O ₂ | * | O ₂ |

*Significance Level 0.05

IV, C, Effect of Chemistry and Forging Practice (cont.)

| | No. Forgings | Carbon | Nitrogen | Hydrogen | Oxygen |
|----------|-----------------|-------------------|-------------------|---------------------|-------------------|
| ≤ 1000°F | 34 | 0.017 to 0.050 | 0.010 to 0.040 | 0.0010 to 0.0055 | 0.134 to 0.192 |
| > 1000°F | 27 | 0.010 to 0.031 | 0.007 to 0.014 | 0.0016 to 0.0085 | 0.140 to 0.200 |

D. EFFECT OF TEST TEMPERATURE

The transition from high-energy oblique fracture to low-energy flat fracture with decreasing temperature is well established from both standard V-notch and precrack Charpy impact data. Figure 9 illustrates the variation in toughness and attending fracture appearance with temperature in the precrack Charpy impact test. The material is Minuteman 6Al-4V titanium tested in the 0.10-in. thickness, aged to two yield-strength levels. Note the increase from 45 to 90% oblique fracture as the temperature was increased from -40 to 320°F in the lower strength condition. The precrack Charpy impact and center-notch (CN) tensile data presented in Figure 10 are from the Supersonic Transport Research Program.* Note that many of the CN-tensile data were invalidated by excessive net-section stress and, consequently, had to be plotted as minimum values. The precrack Charpy impact test, on the other hand, indicated increasing fracture toughness with increasing temperature.

In Phase I of the current data collection, two chambers (SNs 2192109 and 673122) were evaluated by precrack Charpy impact tests at both room temperature and at 200 and 320°F. The test results are presented in Figure 11. Note that at room temperature, the slow bend test result was markedly lower than the impact test result; whereas, at elevated temperature, there was little or no difference between the slow-bend and impact test results. This difference in material behavior when tested in slow bend and impact is believed to be the result of a complex interplay of adiabatic deformation at the crack tip when tested in impact, and time-dependent metallurgical effects (such as the diffusion of hydrogen) when tested in slow bending.**

Additional plots of data based on tests of the body cylinders of three successfully hydrotested Minuteman 6Al-4V titanium chambers are presented in Figure 12. Note that in chamber 2191093, at room temperature the slow-bend

*"Thick-Section Fracture Toughness," a Boeing-North American joint venture, under Federal Aviation Contract AF 33(657)-11461.

**Hartbower, C. E., "Materials Sensitive to Slow Rates of Straining" Scheduled for Presentation at the ASTM Symposium on Testing by Impact, Annual Meeting, Atlantic City, June 1969.

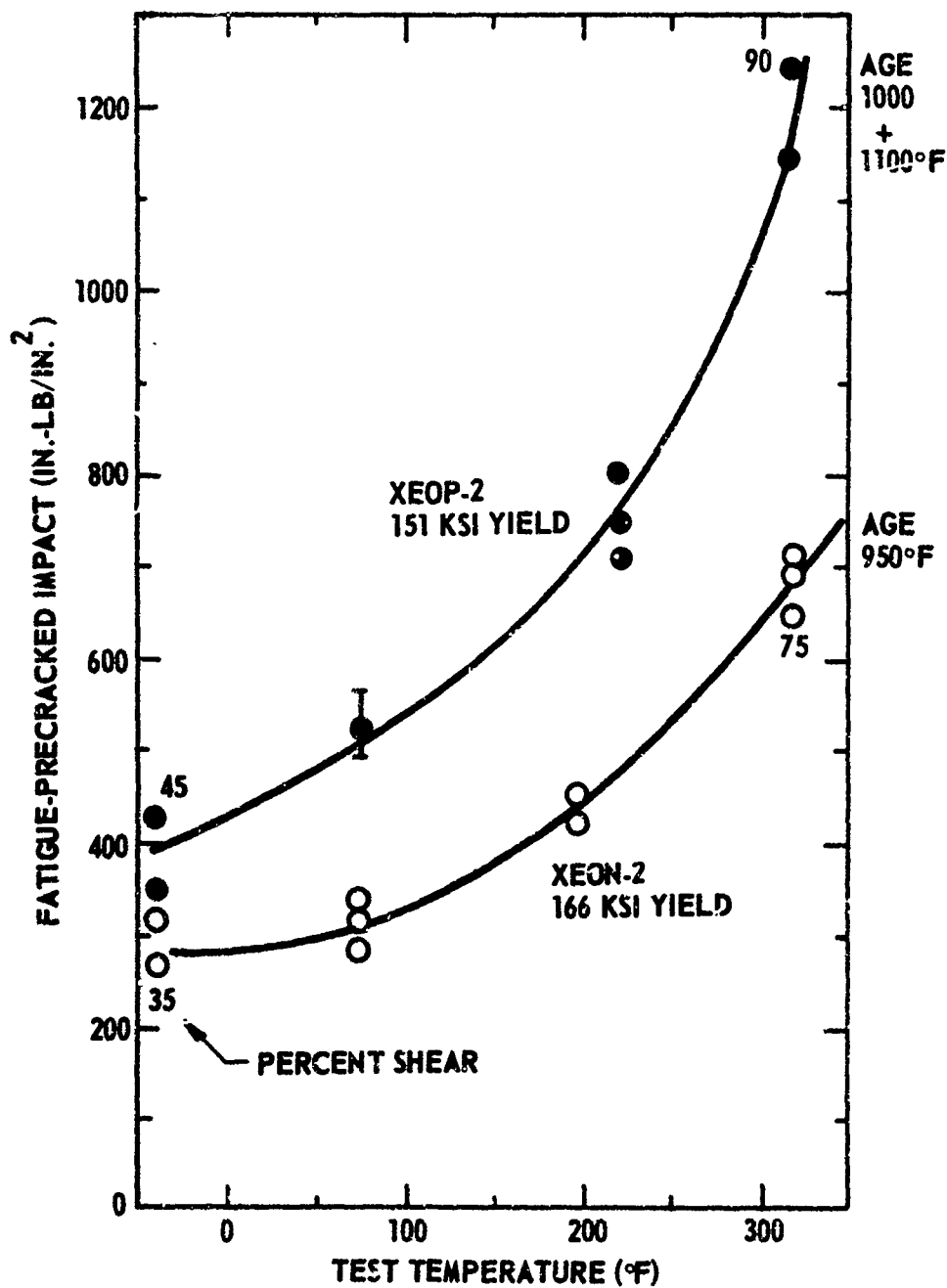


Figure 9. Effect of Temperature on the Precrack Charpy Impact W/A Value in 6Al-4V Titanium

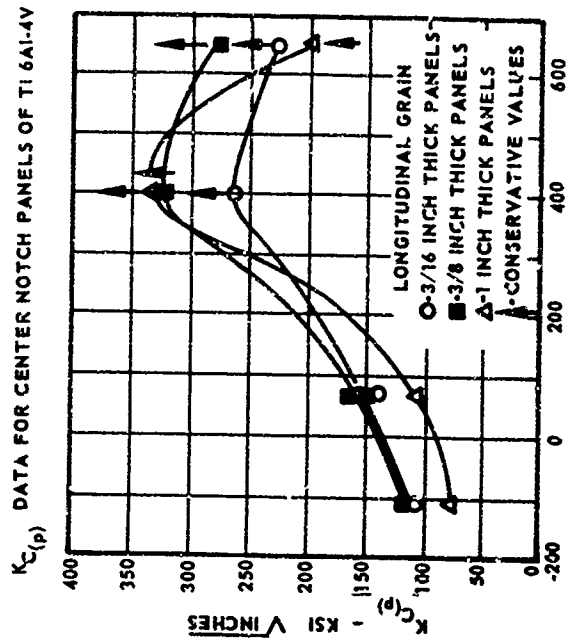
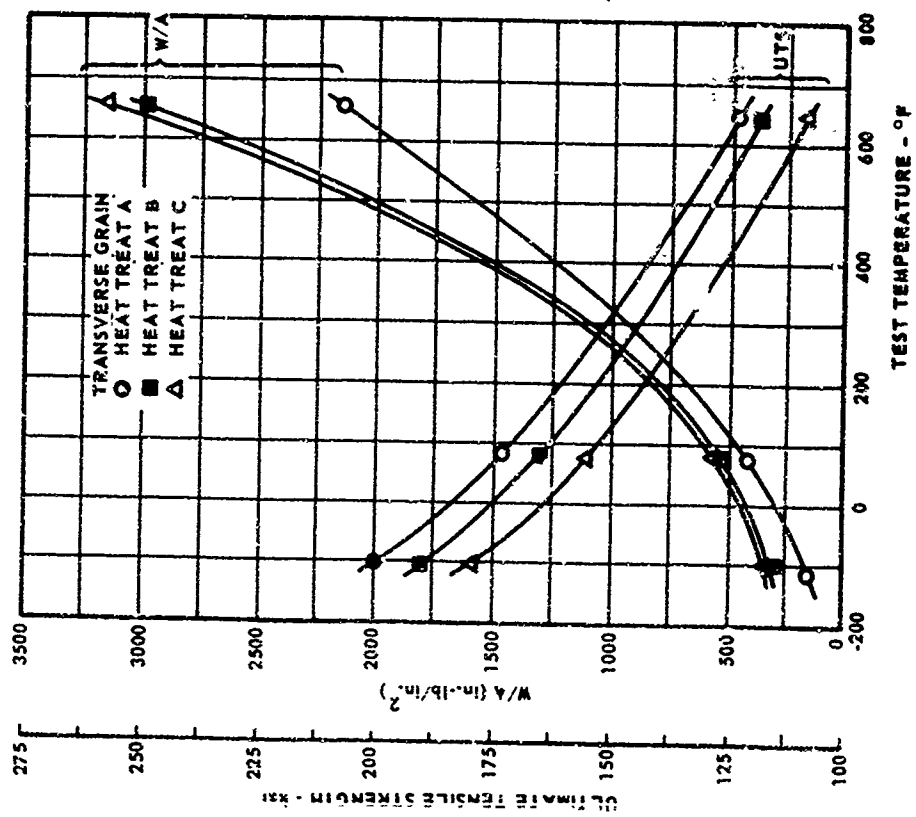


Figure 10. Effect of Temperature on Piecrack Charpy Impact and CN-Tensile Tests in 6Al-4V Titanium

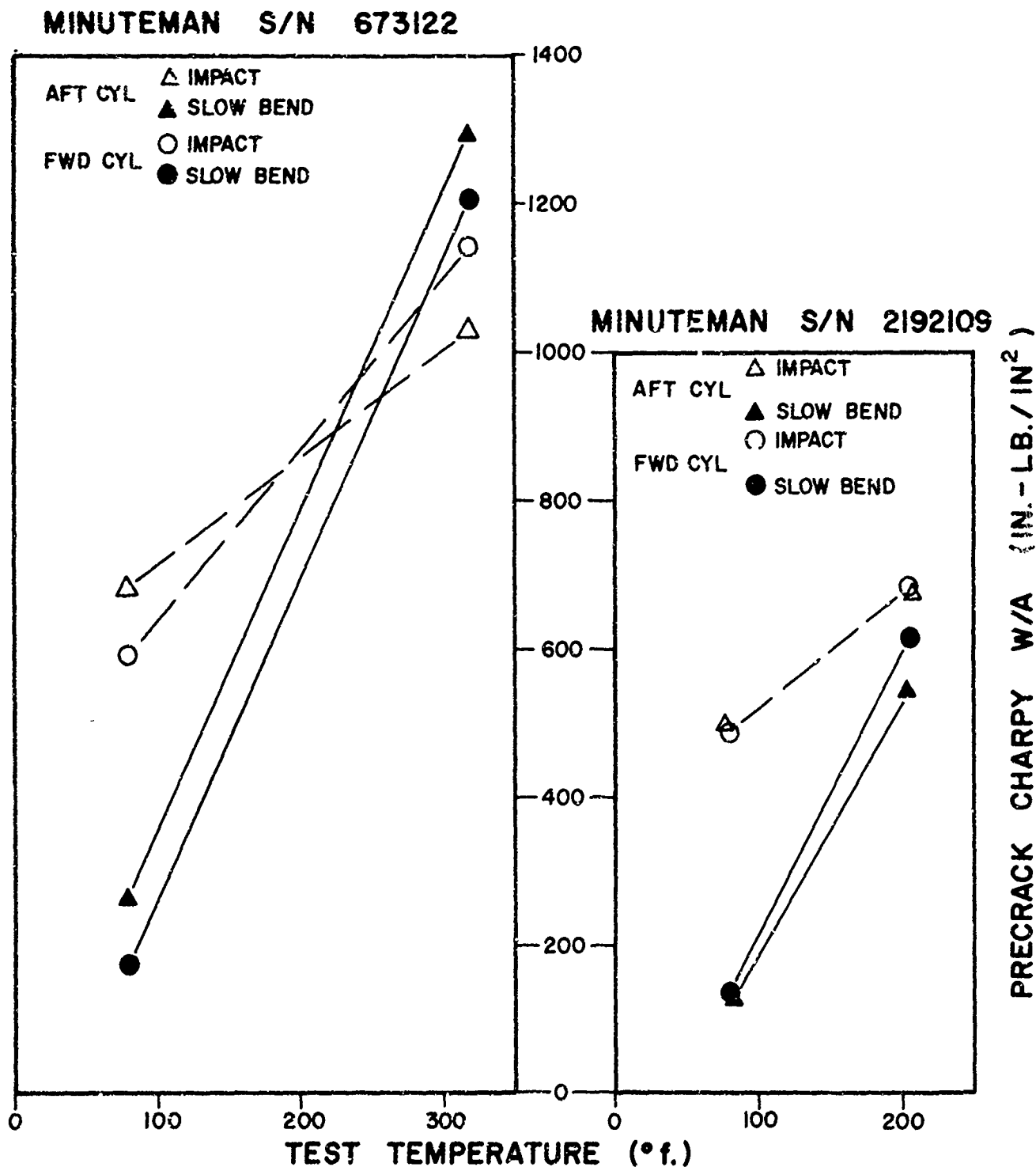


Figure 11. Effect of Temperature on Precrack Charpy Slow-Bend and Impact Tests of 6Al-4V Titanium Chambers 673122 and 2192109

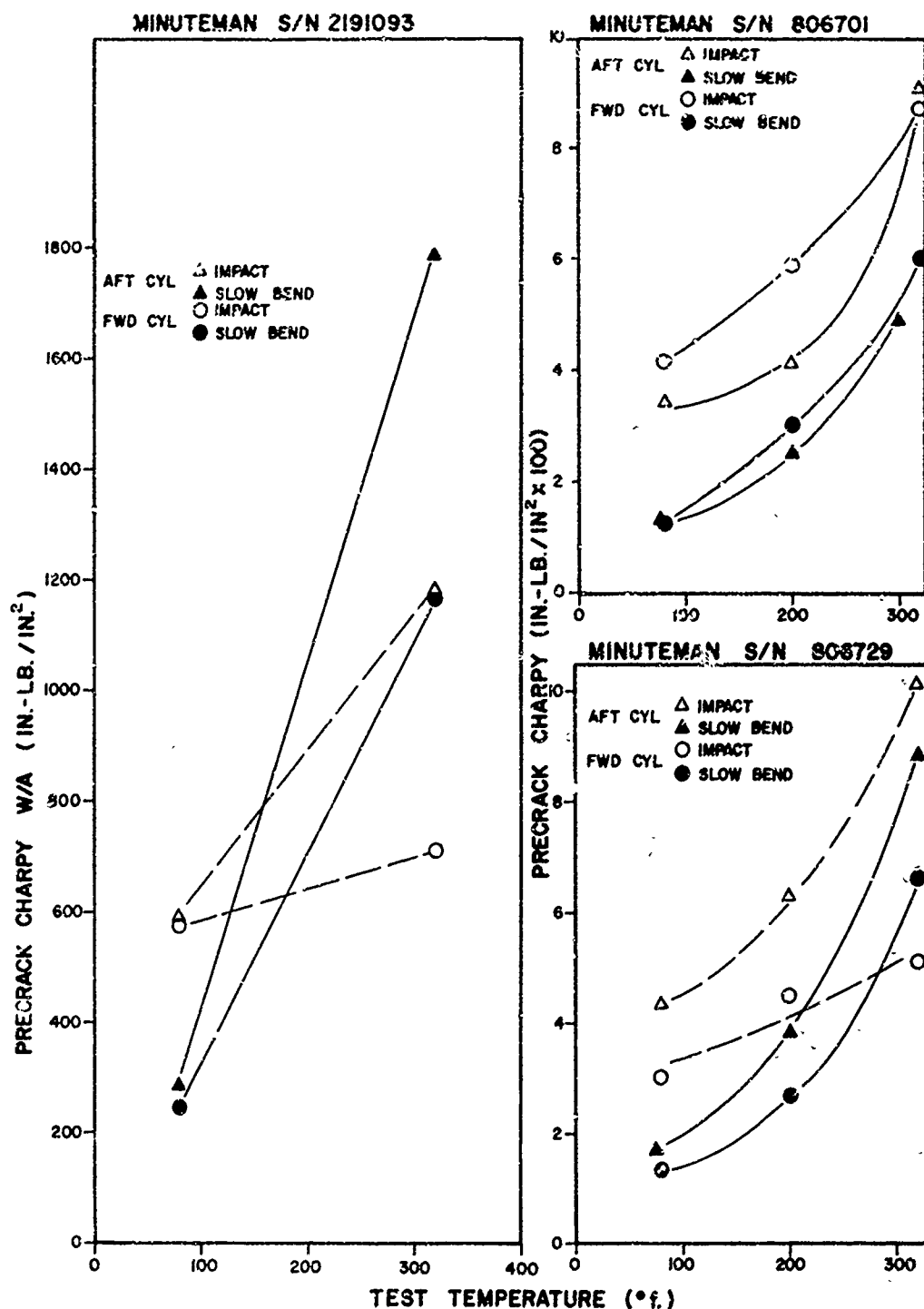


Figure 12. Effect of Temperature on the Toughness of Forgings in Chambers 2191093, and 806729

IV, D, Effect of Test Temperature (cont.)

W/A value was significantly lower than that obtained in impact; whereas, at 320°F, there was a complete reversal of the trend. In chambers 806701 and 806729, the behavior was different in that the slow-bend test result was lower than that obtained in impact in three out of the four body cylinders at all temperatures tested. It is suspected that the forging practice used in manufacturing the body cylinders of chambers 806701 and 806729 was different from that used for 2191093; however, information on the forging practice for these chambers was not available.

Figure 13 is a composite of the precrack Charpy impact transition curves for 55 chamber components tested in the current data collection. The curves for each individual forging will be found in Appendix I. From Figure 13, it will be noted that the band encompassing the data was wide, indicating considerable variation in toughness from component to component at any given temperature. At -40°F, the W/A values ranged from approximately 200 to 600 in.-lb/in.²; at room temperature, from about 250 to 800 in.-lb/in.²; at 200°F from about 400 to 1100 in.-lb/in.²; and at 320°F, from about 600 to 1500 in.-lb/in.². The average W/A values at each temperature level are shown in the following summary tabulation:

| <u>Test Temperature, °F</u> | <u>Number Averaged</u> | <u>Arithmetical Mean</u> |
|---------------------------------|----------------------------|------------------------------|
| -40 | 51 | 380 |
| RT | 149 | 480 |
| 200 | 53 | 650 |
| 320 | 52 | 920 |

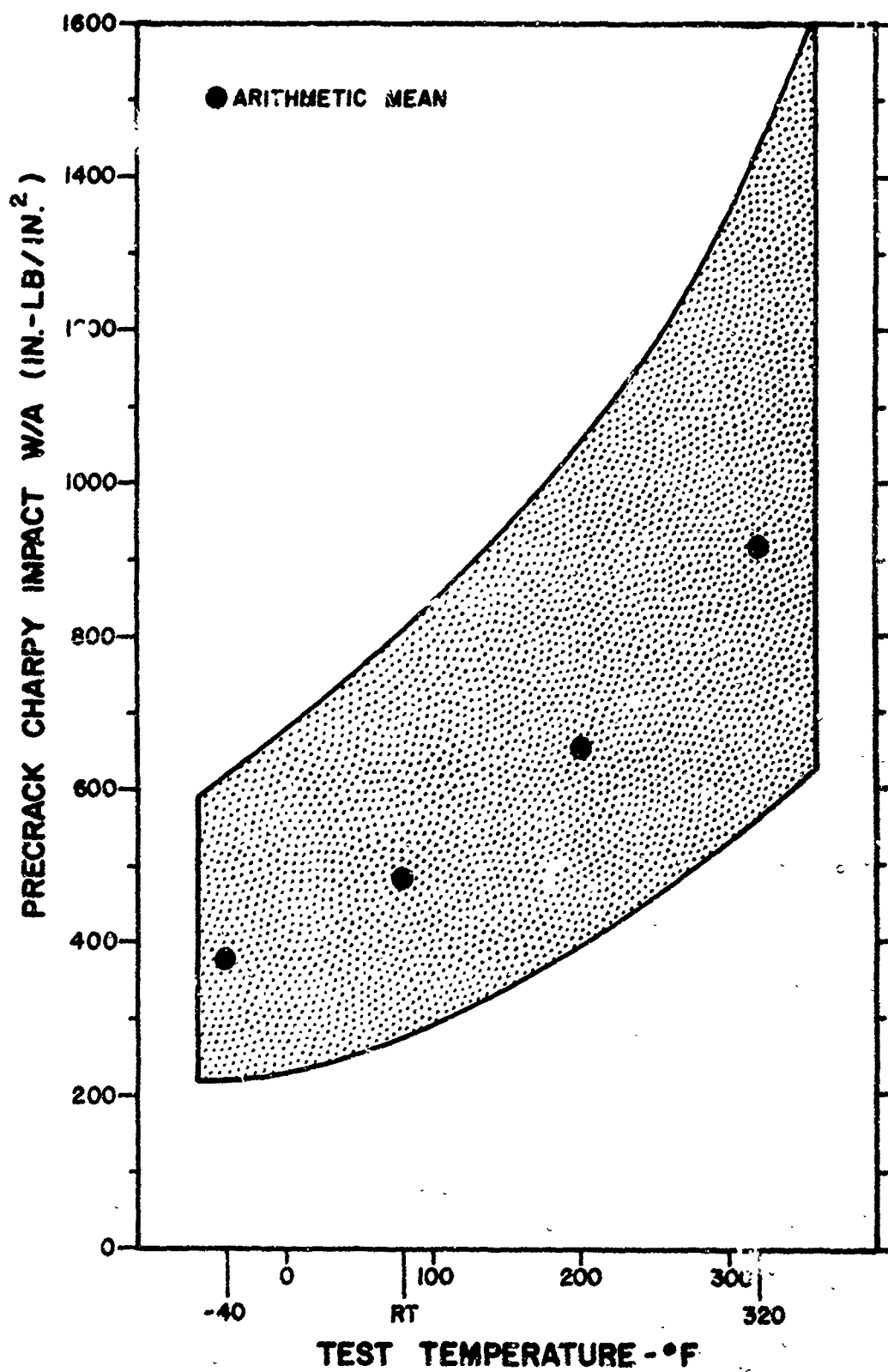


Figure 13. Composite Precrack Charpy Impact Transition Curves for 55 6Al-4V Titanium Forgings

IV, Discussion of Results (cont.)

E. CORRELATION OF FRACTURE TOUGHNESS AND CHAMBER PERFORMANCE

1. Correlation Concepts

When an existing flaw reaches the critical stress intensity under plane-strain conditions (K_{IC}), the flaw will become unstable (pop-in) but then in some chambers be arrested by plane-stress crack toughness on penetrating the chamber wall ($c_{cr} > B$). The fact that there was relatively little variation in plane-strain crack toughness (K_{IC}) as measured in 109 forgings, whereas, there was considerable variation in plane-stress crack toughness (K_C) suggests that K_C is the controlling property in 6Al-4V Minuteman chamber performance.

If a given chamber were to have a defect in each component, and if each defect were of the same size and orientation and equally stressed, on increasing the pressure the lowest-toughness component would reach a critical stress intensity first and fail the chamber. In a real situation, where some components contain flaws and others do not, the component with the highest stress-intensity flaw will fail the chamber, assuming the flawed components all have the same toughness. If the flawed components are of unequal toughness, the first component to reach a critical crack size will fail the chamber. Similarly, if only one component contains a defect, when that defect is stressed to the critical stress intensity, the chamber will fail. Thus, if a given chamber contains components of different fracture toughness, the component containing a flaw of critical size will fail the chamber even if that component has the highest toughness of any of the chamber components. On the other hand, if the critical crack size is not reached by the time the proof test is completed, the chamber will pass the proof test even though the crack may have been enlarged in the process.

Most of the prematurely failed Minuteman chambers contained a flaw which from discoloration was known to have existed before going into proof test. If the original flaw were to pop-in and then be arrested as a result of the plane-stress critical-crack-size being greater than twice the material thickness ($c > B$), there would have to be additional slow crack growth before catastrophic failure of the chamber. In other words, the arrested crack after pop-in would have to grow to the critical crack size under plane-stress conditions. The fact that some chambers failed while under constant load (at proof pressure) indicates that slow crack growth (probably stress corrosion cracking) did in fact occur. One way to verify this would be to calculate the failure hoop stress based on the hear-stained (original) defect dimensions and the mean plane-strain crack toughness ($K_{IC} = 39 \text{ ksi-in.}^{1/2}$) from the equation

$$K_{IC}^2 = 1.21\pi F^2 a/Q$$

IV, E, Correlation of Fracture Toughness and Chamber Performance. (cont.)

where F is the hoop stress at failure and a/Q the normalized crack depth. If the calculated value of stress were found to agree with failure hoop stress, it could be assumed that there was little, if any, slow crack growth. If, on the other hand, there were appreciable slow crack growth before plane-strain pop-in, the calculated value of hoop stress based on the heat-stained crack dimensions would be larger than the observed failure hoop stress. Because Q is a function of the ratio of failure stress to yield strength, iteration would have been required for calculating the failure hoop stress. To avoid this, the critical stress intensity (K_{Ic}) was calculated instead of the hoop stress, using the actual hoop stress at failure and the original flaw dimensions. With an appreciable amount of slow crack growth before pop-in, the calculated value of K_{Ic} would be low compared with the mean plane-strain crack toughness ($K_{Ic} = 39 \text{ ksi-in.}^{1/2}$) as determined in Phase I of this contract.

Figures 14 and 15 provide a graphical solution of the equation

$$K_{Ic}^2 = 1.21\pi F^2 a/Q$$

for surface part-through cracks. Table XIII presents the yield strengths as measured from integral-ring material stress-relieved with the chamber.

2. Premature-Failure Case Histories

Of the 14 Minuteman chambers selected for the data collection, nine were premature proof-test failures. The following paragraphs present the salient facts relating to the failures, including the hoop stress at which failure occurred, and the nature and location of the originating defect. In some instances, a limited amount of precontract fracture testing was done on the casualty chamber; these data also are presented.

a. Chamber R26

In May 1962, chamber R26 failed during proof test with the fracture origin in the adapter of the forward closure. The failure occurred after 15 sec at maximum pressure (96-ksi hoop stress at the fracture origin). Examination of the fracture surfaces revealed a surface crack in the forward adapter 0.2 in. forward of the forward girth weld, near the heat-affected zone of the weld; the defect was approximately 0.10 in. deep and 0.18 in. long.

Uniaxial and PTC-tensile specimens were taken from the forward cylinder of chamber R26 across the forward girth weld opposite the origin of failure. The uniaxial tensile specimens from the forward cylinder

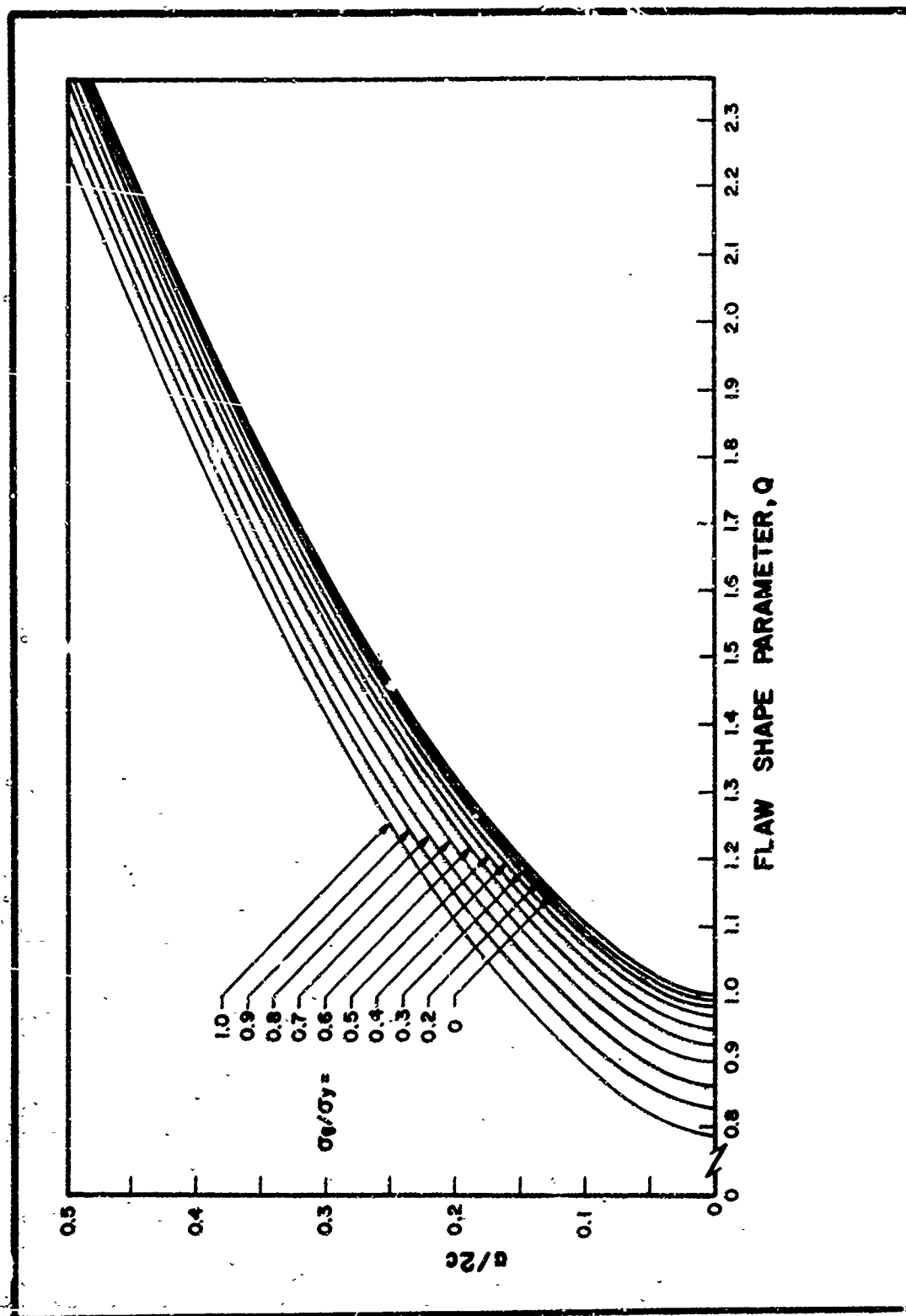


Figure 14. Flaw-Shape Parameter for Surface Embedded Flaws

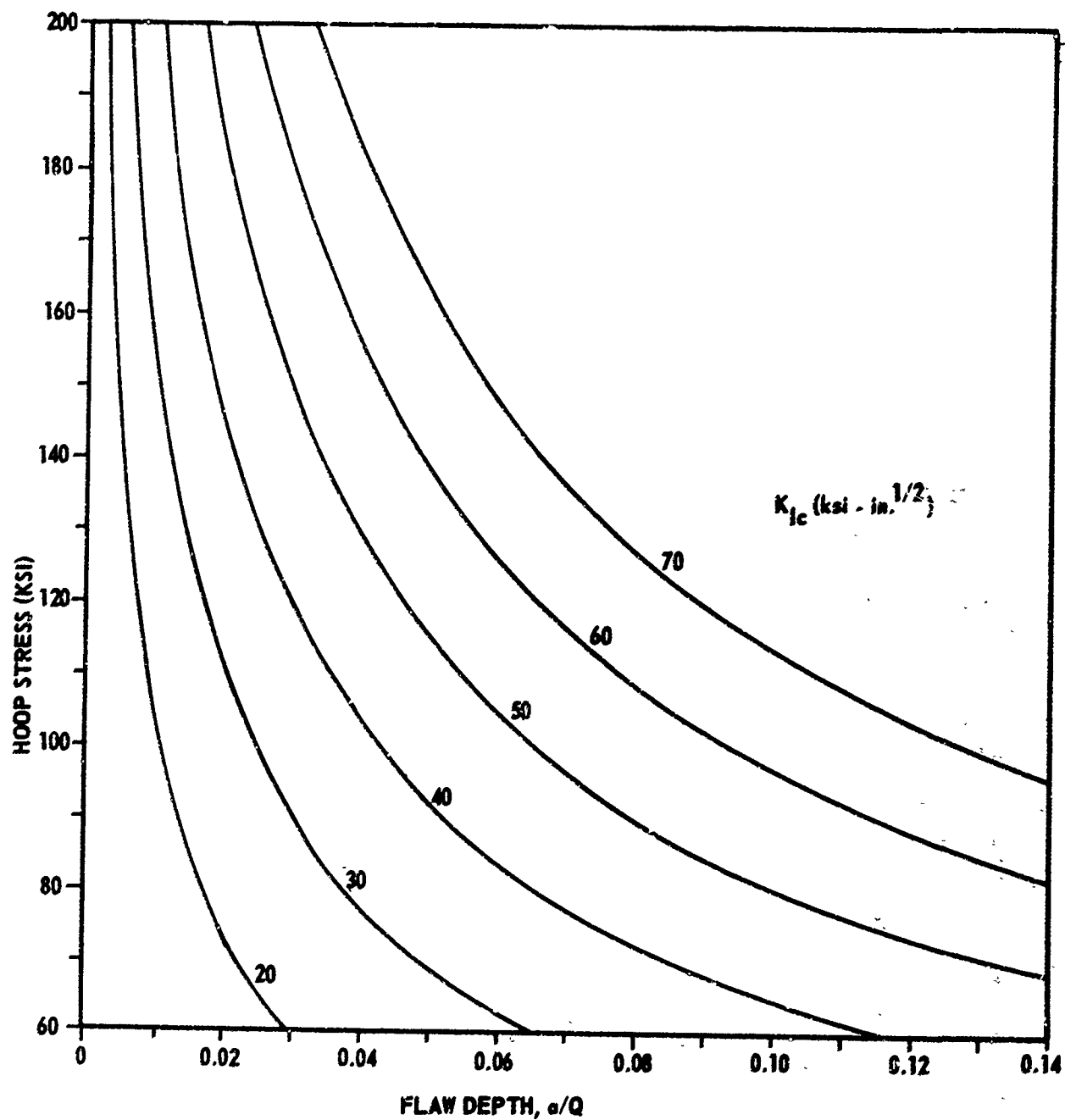


Figure 15. Hoop Fracture Stress as a Function of Normalized Flaw Depth for Various Plane-Strain Critical-Stress-Intensity Levels .

TABLE XIII

TENSILE PROPERTIES OF MINUTEMAN COMPONENTS
AFTER CHAMBER STRESS RELIEF

| <u>Chamber</u> | <u>Fwd Closure</u> | | <u>Fwd Cylinder</u> | | <u>Aft Cylinder</u> | | <u>Aft Flange</u> | |
|----------------|--------------------|-------------|---------------------|-------------|---------------------|-------------|-------------------|-------------|
| | <u>Yield</u> | <u>Ult.</u> | <u>Yield</u> | <u>Ult.</u> | <u>Yield</u> | <u>Ult.</u> | <u>Yield</u> | <u>Ult.</u> |
| | ksi | ksi | ksi | ksi | ksi | ksi | ksi | ksi |
| R26 | 167 | 178 | 165 | 173 | 165 | 177 | 168 | 174 |
| BL26 | 160 | 170 | 158 | 167 | 164 | 175 | 166 | 175 |
| R369 | 167 | 178 | 162 | 171 | 167 | 175 | 164 | 176 |
| R490 | 164 | 176 | 161 | 172 | 168 | 176 | 162 | 174 |
| R512 | 162 | 175 | 166 | 175 | 164 | 174 | 167 | 176 |
| R516 | 164 | 177 | 165 | 176 | 165 | 174 | 162 | 174 |
| R543 | 159 | 169 | 159 | 173 | 163 | 175 | 163 | 169 |
| 673078 | 168 | 183 | 170 | 184 | 164 | 176 | 164 | 180 |
| 2191456 | 169 | 179 | 166 | 177 | 158 | 168 | 164 | 176 |
| 2192109 | 166 | 176 | 167 | 174 | 165 | 173 | 166 | 173 |

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

near the fracture origin exhibited exceptionally low elongation*; examination of the tensile-specimen fracture surfaces revealed thumbnail-shaped spots of oxidation, surrounded by flat fracture. The defects were approximately 0.015 in. by 0.010 in. Metallography revealed no microstructural abnormality. The defects were in the surface corresponding to the ID surface of the chamber. In that the test specimens were heat-straightened (900°F for 2 hr) prior to testing, the defects could have been produced by the heat-straightening operation, or they could have been present in the ID surface of the chamber prior to heat-straightening the test specimens.

The results of the part-through-crack (PTC) tensile tests are presented in Table XIV, together with the K_{Ic} value calculated from the flaw dimensions and failure hoop stress in the prematurely burst chamber. If compared with the data from 109 forgings as reported in Appendix B of Volume I ($K_{Ic} = 39.1 \text{ ksi-in.}^{1/2}$ with a standard deviation of $1.6 \text{ ksi-in.}^{1/2}$), the K_{Ic} values obtained from PTC-tensile tests of the body cylinders of chamber R26 were somewhat above the population mean value of $39 \text{ ksi-in.}^{1/2}$ (the upper limit for two sigma is $42.2 \text{ ksi-in.}^{1/2}$); whereas, the K_{Ic} value of $38.6 \text{ ksi-in.}^{1/2}$ calculated from the chamber itself was in agreement with the mean value.

The following summary of room-temperature precrack Charpy impact W/A values showed that the forward adapter (chamber fracture origin) had appreciably lower plane-stress fracture toughness than the body cylinders or the aft flange.

| <u>Forward Closure</u> | | <u>Body Cylinders</u> | | <u>Aft Flange</u> |
|------------------------|--------------------|-----------------------|-------------------|-------------------|
| <u>Dome</u> | <u>Adapter</u> | <u>Forward</u> | <u>Aft</u> | |
| 443 to 623 | 318 to 484 | 691 to 1010 | 663 to 938 | 719 to 883 |
| Av (12) <u>494</u> | Av (12) <u>426</u> | Av (9) <u>841</u> | Av (7) <u>847</u> | Av (3) <u>822</u> |

The summary includes the axial-notch-direction precrack Charpy tests from Phase I (see Appendix D of Volume I).

b. Chamber R41

In November 1962, chamber R41 failed in the forward cylinder at 124-ksi hoop stress during rising load. Examination of the fracture surfaces revealed a metallurgical defect in the surface of the 0.10-in.-thick wall, which consisted of a void surrounded by massive alpha titanium; the embrittled zone was approximately 0.050 in. in diameter. Figure 16 shows the fracture surface containing the defect, together with a photomicrograph showing the massive alpha associated with the defect.

*Allison Monthly Status Report No. 8 for 15 March through 15 April 1963.

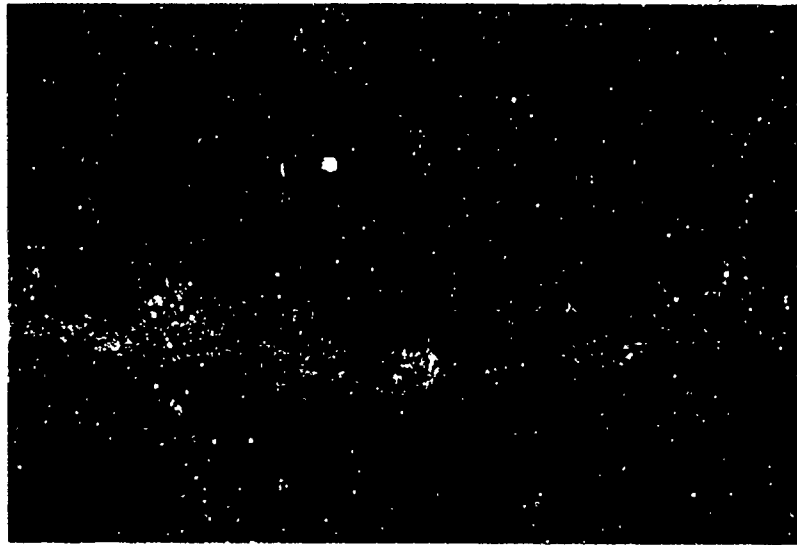
TABLE XIV

PTC-TENSILE TESTS OF 6Al-4V TITANIUM FROM
MINUTEMAN CHAMBER R26

| Component Tested | r _{ty} * | Crack Dimensions | | | Gross Stress F | Ratio F/F _{ty} | Shape Parameter Q | Normal-ized Depth a/Q | Critical Stress Intensity K _{Ic} (ksi-in. ^{1/2}) |
|----------------------|-------------------|------------------|-----------|------------|----------------|-------------------------|-------------------|-----------------------|---|
| | | Depth a | Length 2c | Shape a/2c | | | | | |
| Fwd Closure Origin** | 167 | 0.10 | 0.18 | 0.56 | 99.6 | 0.60 | 2.55 | 0.039 | 38.6 |
| Fwd Cyl Near Origin | 165 | 0.042 | 0.100 | 0.420 | 151.6 | 0.92 | 1.92 | 0.022 | 43 |
| | | 0.040 | 0.102 | 0.392 | 151.7 | 0.92 | 1.83 | 0.022 | 43 |
| | | 0.050 | 0.203 | 0.246 | 126.8 | 0.77 | 1.32 | 0.038 | 48 |
| | | 0.054 | 0.203 | 0.266 | 118.6 | 0.72 | 1.39 | 0.039 | 45 |
| | | 0.050 | 0.200 | 0.250 | 126.5 | 0.77 | 1.33 | 0.038 | 47 |
| Aft Cyl Location 1 | 165 | 0.040 | 0.107 | 0.374 | 156.4 | 0.95 | 1.71 | 0.023 | 46 |
| | | 0.034 | 0.098 | 0.347 | 155.6 | 0.94 | 1.70 | 0.020 | 43 |
| | | 0.056 | 0.205 | 0.273 | 135.8 | 0.82 | 1.40 | 0.040 | 52 |
| | | 0.058 | 0.210 | 0.276 | 135.4 | 0.82 | 1.40 | 0.041 | 52 |
| Aft Cyl Location 2 | 165 | 0.035 | 0.102 | 0.343 | 152.4 | 0.92 | 1.61 | 0.022 | 43 |
| | | 0.037 | 0.108 | 0.343 | 152.8 | 0.93 | 1.61 | 0.023 | 45 |
| | | 0.053 | 0.206 | 0.257 | 118.3 | 0.72 | 1.38 | 0.038 | 45 |
| | | 0.055 | 0.207 | 0.266 | 117.9 | 0.71 | 1.42 | 0.039 | 45 |

*Yield strength in integral-test-ring material aged with the chamber.

**Calculation of critical stress intensity based on failure hoop stress and flaw dimensions as measured in the failed chamber.



8X



100X

Figure 16. Fracture Origin and Associated Microstructure in Chamber R41

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

An estimate was made of the plane-strain (K_{Ic}) fracture toughness on the basis of the flaw dimensions

$$a = 0.050 \text{ in.}, 2c = 0.10 \text{ (estimated)}, a/2c = 0.50$$

and the hoop stress at failure

$$F = 124 \text{ ksi}, F/F_{ty} = 124/156.4 = 0.79$$

the flaw-shape parameter and normalized flaw depth were

$$Q = 2.28, a/Q = 0.022$$

which give a plane-strain crack toughness from the chamber itself of

$$K_{Ic} = \underline{36 \text{ ksi-in.}^{1/2}}$$

This K_{Ic} value is reasonably close to the mean value reported in Volume I for 109 forgings (the lower limit for two sigma is 35.8 ksi-in.^{1/2}).

The following tabulation summarizes the room-temperature precrack Charpy impact W/A values obtained from chamber R41:

| <u>Forward Closure</u> | | <u>Body Cylinder</u> | | <u>Aft Flange</u> |
|------------------------|-------------------|----------------------|-------------------|-------------------|
| <u>Dome</u> | <u>Adapter</u> | <u>Forward</u> | <u>Aft</u> | |
| 527 to 609 | 352 to 404 | 515 to 590 | 656 to 740 | 379 to 496 |
| Av (3) <u>578</u> | Av (3) <u>377</u> | Av (3) <u>550</u> | Av (3) <u>713</u> | Av (3) <u>428</u> |

The impact test results from the forward cylinder (not from the immediate vicinity of the metallurgical defect) gave higher W/A values than either the forward or aft adapters. If there had been sizable defects in the latter components, they should have failed the chamber before the forward cylinder. The aft cylinder had the highest toughness of the various components in chamber R41.

c. Chamber BL26

In January 1964, chamber BL26 failed after a 4-sec hold at proof pressure (110-ksi hoop stress at the fracture origin). Examination of the fracture surfaces revealed a semielliptical crack on the inside of the aft adapter in the reinforced section adjacent to the aft girth weld, but outside the weld heat-affected zone; the defect initiating failure was 0.030 in. deep and 0.150 in. long. A second crack, 0.040 in. deep and 0.066 in. long,

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

was detected adjacent to the forward girth weld on the inside surface of the forward closure. From an examination of the fracture surfaces, it was postulated that the failure originated from the crack in the aft adapter, and proceeded forward and aft; and that the second crack originated a secondary failure in the weld-reinforced area of the forward dome. The two fractures intersected approximately 5 in. aft of the forward girth weld. After the failure, inspection revealed 16 additional cracks; all except one extended partially into weld heat-affected zone. The largest of these additional cracks was 0.040 in. deep and 0.060 in. long.

An estimate was made of the plane-strain (K_{Ic}) fracture toughness based on the measured crack dimensions in the fracture-origin component

$$a = 0.080 \text{ in.}, 2c = 0.150, a/2c = 0.534$$

and the chamber hoop stress at failure

$$F = 110 \text{ ksi}, F/F_{ty} = 110/166 = 0.663$$

The flaw-shape parameter and normalized crack depth were

$$Q = 2.43, a/Q = 0.0329$$

which gave a plane-strain crack toughness from the chamber itself of

$$K_{Ic} = \underline{39 \text{ ksi-in.}^{1/2}}$$

This K_{Ic} value is in agreement with the mean value reported in Volume I for 199 forgings.

The following tabulation summarizes the room-temperature precrack Charpy impact W/A values obtained from the reinforced sections next to the various girth welds:

| <u>Forward Adapter</u> | <u>Body Cylinders</u> | | <u>Aft Adapter</u> |
|------------------------|-----------------------|-------------------|--------------------|
| | <u>Forward</u> | <u>Aft</u> | |
| 405 to 432 | 429 to 559 | 418 to 541 | 380 to 623 |
| Av (2) <u>419</u> | Av (4) <u>486</u> | Av (4) <u>461</u> | Av (4) <u>460</u> |

Note that the Charpy tests of material from the reinforced sections adjacent to each of the girth welds gave W/A values that were not greatly different from one component to another.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

With the fracture toughness of the various components nearly the same, the fracture origin was determined by the location of the largest defect present; the largest flaw was located in the reinforced section of the aft closure next to the G3 weld. It is interesting to note that all of the flaws were in the ID surface, all were oriented in the chamber-axial direction, and all except one extended partially into the HAZ of the girth welds.

d. Chamber 2191456

In March 1963, chamber 2191456 failed during rising load at a pressure of 457 psig (75-ksi hoop stress at the fracture origin). The failure origin as shown in Figure 17* was located in a repair of the forward girth weld. Examination of the fracture surfaces revealed porosity in the weld-repair area with two closely spaced pores (0.045-in.-dia and 0.020-in.-dia pores, one above the other, 0.004 in. apart) at approximately mid-thickness, resulting in an embedded flaw approximately 0.069 in. deep and 0.045 in. long in air-contaminated weld metal. Precrack Charpy tests were made at Aerojet-Sacramento of the weld metal in the forward girth weld both near the fracture origin and away from the fracture origin. The data presented in the following tabulation clearly show an embrittled condition near the fracture origin**.

| | Precrack Charpy (in.-lb/in. ²) Tests of Weld-Fusion-Zone | | | |
|------------------|--|------------------------------------|------------------------------------|------------------------------------|
| | Slow Bend | | Impact | |
| | RT | 320°F | RT | 320°F |
| Near Origin | 837 to 951 Av (2) <u>894</u> | 1024 to 1161 Av (2) <u>1092</u> | 721 to 757 Av (3) <u>742</u> | 1264 to 1816 Av (3) <u>1473</u> |
| Away from Origin | 1147 to 1164 Av (2) <u>1156</u> | 1663 to 1954 Av (2) <u>1808</u> | 1130 to 1370 Av (3) <u>1256</u> | 2010 to 2490 Av (3) <u>2210</u> |

*Metallurgical Failure Analysis of Second-Stage Minuteman Rocket Motor Case 2191456, Ti-6Al-4V Alloy, Hellmann, V. L., Allison Materials Research Lab Report 63FA4, 25 March 1963.

**The fracture-origin location in the forward girth weld of chamber 2191456 had appreciably lower toughness than any weld tested to date. The following table presents a comparison between the fracture origin in chamber 2191456 and welds in successfully hydrotested chambers.

| Motor | Weld Yield, ksi | Fracture Toughness, in.-lb/in. ² |
|---------|-----------------|--|
| 2191456 | 155 | 742 |
| 673196 | 147 | 1077 |
| 673097 | 144 | 1366 |
| 673122 | 123 | 1577 |

ID

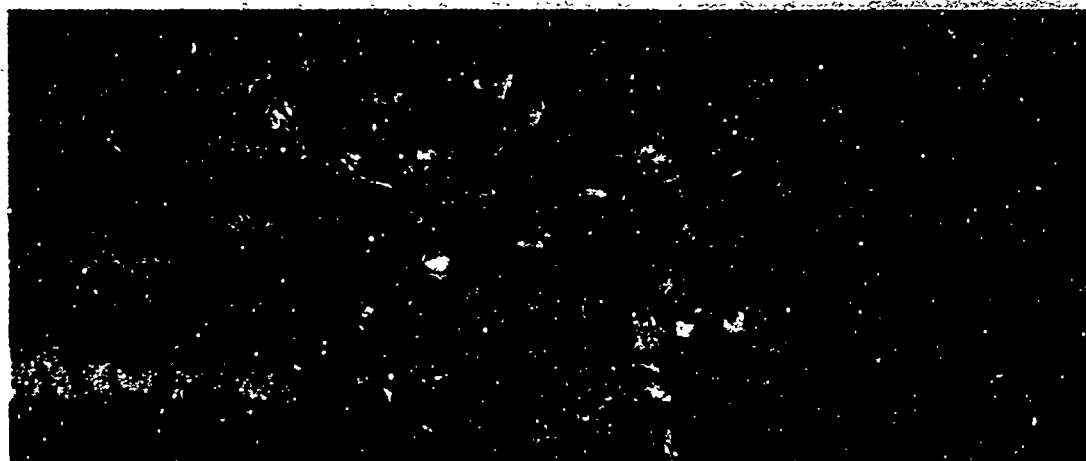


(Neg No. 8-09276)

OD

(Magn: 3X)

ID



(Neg No. 8-09274)

OD

(Magn: 9X)

Figure 17. Fracture Origin in Forward Girth Weld of Chamber.
2191456

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

An estimate was made of the plane-strain (K_{Ic}) fracture toughness assuming interaction of the porosity to form a single penny-shaped internal flaw of dimensions.

$$2a = 2c = 0.069, a/2c = 0.5$$

and a chamber hoop stress at failure

$$F = 75 \text{ ksi}, F/F_{ty} = 75/155 = 0.484$$

the flaw-shape parameter and normalized crack depth were

$$Q = 2.36, a/Q = 0.0146$$

which gave a plane-strain crack toughness from the chamber itself of

$$K_{Ic} = \underline{16 \text{ ksi-in.}^{1/2}}$$

This value of K_{Ic} seems anomalously low; however, titanium weld metal in the vicinity of porosity can be expected to be contaminated*.

The following tabulation summarizes the PCI-test results obtained in chamber 2191456 (the body-cylinder data include the axial-notch-direction W/A values obtained in Phase I):

| <u>Forward Closure</u> | | <u>Body Cylinder</u> | | <u>Aft Closure</u> |
|------------------------|-------------------|----------------------|-------------------|--------------------|
| <u>Dome</u> | <u>Adapter</u> | <u>Forward</u> | <u>Aft</u> | <u>Flange</u> |
| 484 to 564 | 411 to 435 | 418 to 537 | 674 to 814 | 638 to 725 |
| Av (3) <u>530</u> | Av (3) <u>423</u> | Av (8) <u>481</u> | Av (9) <u>756</u> | Av (3) <u>674</u> |

Note that the precrack Charpy impact tests of the components on either side of the G1 weld showed the lowest fracture toughness in the chamber. Unfortunately, material was not available for testing the reinforced sections of the G1 weld.

a. Chamber R369

In September 1966, chamber R369 failed during rising load at a pressure of 380 psig (80-ksi hoop stress at the fracture origin).

*Hartbower, C. E., "Fusion Welding High-Strength Titanium Sheet", Proceedings of the 7th Sagamore Ordnance Materials Research Conference, 16-19 August 1960, p. III-101.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

The fracture was located in the aft cylinder just outside the reinforced section of the aft (G3) weld, and was readily identified by a discolored semielliptical area at the ID surface approximately 0.25 in. long, which very nearly penetrated the wall thickness. The discoloration on the fracture face (Figure 18) showed the crack to have been open during one of the heat treatments.

An estimate was made of the plane-strain (K_{Ic}) fracture toughness on the basis of the measured flaw dimensions in the failed chamber

$$a = 0.10, 2c = 0.25, a/2c = 0.40$$

and the hoop stress in the chamber at failure

$$F = 80 \text{ ksi}, F/F_{ty} = 0.49$$

the flaw-shape parameter and normalized crack depth were

$$Q = 1.92, a/Q = 0.052$$

which, with Smith's approximation of the stress-intensity magnification factor (M_K) for a deep surface flaw of $a/2c = 0.4$ ($M_K = 1.1$) gave a plane-strain crack toughness from the chamber test of

$$K_{Ic} = 42 \text{ ksi-in.}^{1/2}$$

This value of K_{Ic} for the failure-origin component of chamber R369 is close to the mean value obtained for 109 forgings in Phase I of this study (two sigma upper limit 42.2 ksi-in.^{1/2}).

The following tabulation summarizes the data obtained from chamber R369, including the test results from the R369 body cylinders tested in Phase I.

| Forward Skirt | Forward Closure | Body Cylinders | | Aft Closure | Aft Skirt |
|---------------|-----------------|----------------|-------------|-------------|------------|
| | | Forward | Aft | | |
| 615 to 636 | 474 to 486 | 302 to 403 | 432 to 528 | 487 to 496 | 606 to 628 |
| Av (3) 629 | Av (3) 446 | Av (12) 340 | Av (12) 480 | Av (3) 492 | Av (3) 615 |

Note that the precrack Charpy impact data for the failure-origin aft cylinder of chamber R369 was somewhat higher than the W/A values obtained from the forward cylinder. The ring-rolled skirts, on the other hand, had appreciably higher toughness than the body cylinders and closures.

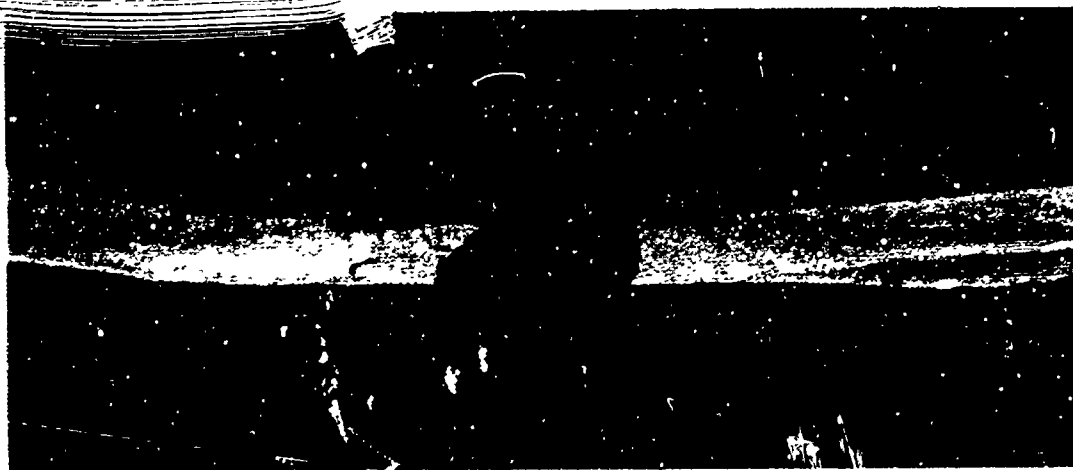
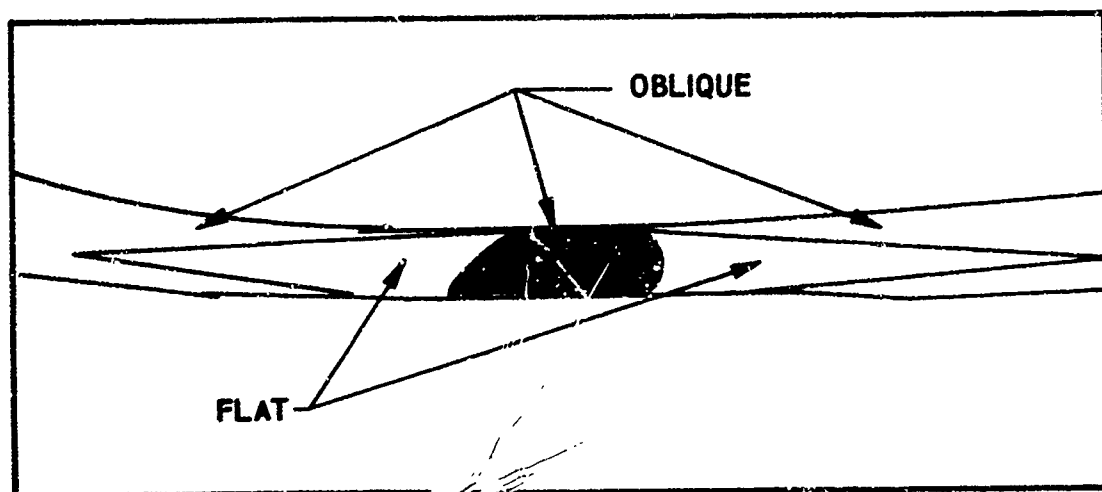


Figure 12. Fracture Origin in Chamber R369

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

The fact that chamber R369 contained a flaw that was very nearly a through crack is of particular interest from the standpoint of the leak-before-burst criterion. The discoloration, as seen in Figure 18, indicates that the flaw developed during heat treatment and, therefore, was in the chamber at the start of the proof test. A very thin shear lip at the OD surface and the tightness of the crack was all that prevented the chamber from leaking at the outset of pressurization. In the 0.10-in.-thick wall, at a yield strength of 166.7 ksi, a W/A value of approximately 1250 in.-lb/in.² would have been required to meet the leak-before-burst criterion. However, this is a special case, in that a defect was already present of greater than "2t" length.

If the defect is treated as a through crack in a wide panel

$$K_c^2 = \pi c_1 F^2$$

where c_1 is the "effective" crack half-length

$$c_1 = c + K_c^2 / 2\pi F_{ty}^2$$

Substituting 100 (W/A) + 6700 for K_c (from Volume I), the measured value of half-crack length ($c = 0.125$ in.) and the yield strength ($F_{ty} = 166.7$ ksi), for W/A = 480 in.-lb/in.²:

$$c_1 = 0.1421$$

Solving for the failure stress using the flat-sheet analysis

$$\begin{aligned} F^2 &= K_c^2 / \pi c_1 \\ &= \underline{82 \text{ ksi}} \end{aligned}$$

which is in excellent agreement with the chamber hoop stress at the fracture origin.

Sullivan and Pierce* in a study of the effect of radius on the bulging and fracture of through-cracked cylindrical pressure vessels, reported that when Irwin's flat-sheet analysis is applied to internally

*Sullivan, T. L. and Pierce, W. S., NASA TN D-4951. December 1968

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

pressured thin-wall, cylindrical vessels, the predicted failure stresses are greater than those obtained experimentally. An equation for predicting the critical hoop fracture stress (F) for an internally pressurized, through-cracked cylinder has been derived by Eiber, et al.* For plane-stress, the Eiber expression states

$$F^2 = K_c^2 / \left[\pi c \sec \left(\frac{\pi F}{2 F_u} \right) \right] \left(1 + \frac{5\pi}{32} \lambda^2 \right) \frac{1}{2} \left(4 - \frac{3-v}{1+v} \right)$$

where F_u is the biaxial ultimate strength, v is Poisson's ratio and

$$\lambda^2 = c^2 \left[12 (1-v^2) \right]^{1/2} / r B$$

where r is the cylinder radius and B is the wall thickness. Substituting

$$c = 0.125$$

$$v = 1/3$$

$$r = 26 \text{ in.}, \text{ and } B = 0.10 \text{ in.}$$

$$F_u = 1.15 \times F_{tu}, \text{ where } F_{tu} = 175 \text{ ksi}$$

$$K_c = 100 (W/A) + 6700, \text{ where } W/A = 480 \text{ in.-lb/in.}^2$$

from Eiber's expression, by iteration the predicted critical hoop fracture stress is

$$F = 79 \text{ ksi}$$

which is in excellent agreement with the chamber hoop stress at the fracture origin.

f. Chamber R490

In June 1967, chamber R490 failed during rising load at a pressure of 600 psig (108-ksi hoop stress at the fracture origin). The failure origin was in the center (G2) girth weld and was attributed to weld contamination as the result of inadequate inert-gas shielding. Pre-crack

*Eiber, R. J., Maxey, W. A., Duffy, A. E., and McClure, G. M., "Behavior of Through-Wall and Surface Flaws in Cylindrical Vessels". Paper presented at the National Symposium on Fracture Mechanics, Lehigh University, Bethlehem, Pa., June 1968.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

Charpy impact specimens were cut transverse to the weld, with the notch centered in the weld fusion zone. The specimens were approximately two feet from the fracture origin. The W/A value at this position in the weld was 1720 in.-lb/in.², which compares favorably with the toughness of the weld metal as measured in other chambers which were successfully hydroburst tested (see Figure 19). Unfortunately, weld metal from the immediate vicinity of the fracture origin was not available for testing. Chemical analysis of the weld metal in the immediate vicinity of the fracture origin revealed a high nitrogen content (1500 ppm).

g. Chamber R512

In September 1967, chamber R512 failed during rising load at a pressure of 590 psig (140 ksi hoop stress at the fracture origin). The fracture origin was located in the forward cylinder 3.5 in. from the center (G2) girth weld, and was readily identified by a discolored semi-elliptical area at the ID surface, approximately 0.03 in. deep and 0.2 in. long. The discoloration on the fracture surface showed the crack to have been open during one of the heat treatments (Figure 20). Examination of the metal in the thumbnail area revealed high interstitial content (approximately 1400 ppm nitrogen), but an essentially normal microstructure.

An estimate was made of the plane-strain (K_{Ic}) fracture toughness that was based on the measured crack dimensions

$$a = 0.03\text{-in.}, 2c = 0.20\text{-in.}, a/2c = 0.15$$

and the failure stress

$$F = 140 \text{ ksi}, F/F_{ty} = 140/166 = 0.84$$

the flaw-shape parameter and normalized crack depth were

$$Q = 1.05, a/Q = 0.029$$

which gave a plane-strain crack toughness from the chamber itself of

$$K_{Ic} = \underline{46 \text{ ksi-in.}^{1/2}}$$

This K_{Ic} value is significantly higher than the population mean of 39 ksi-in.^{1/2} (two sigma upper limit 42.2 ksi-in.^{1/2}) obtained for the 109 forgings reported in Volume I, and appears anomalously high considering that two laboratories measured 1400 ppm nitrogen in the immediate vicinity of the crack while it was only 112 ppm 1 in. away from the crack². Figure 20 shows the heat-stained

²Motal, D., "Metallurgical Analysis of Hydrotest Failure R512,"
DM:cp:M-2139, 23 October 1967.

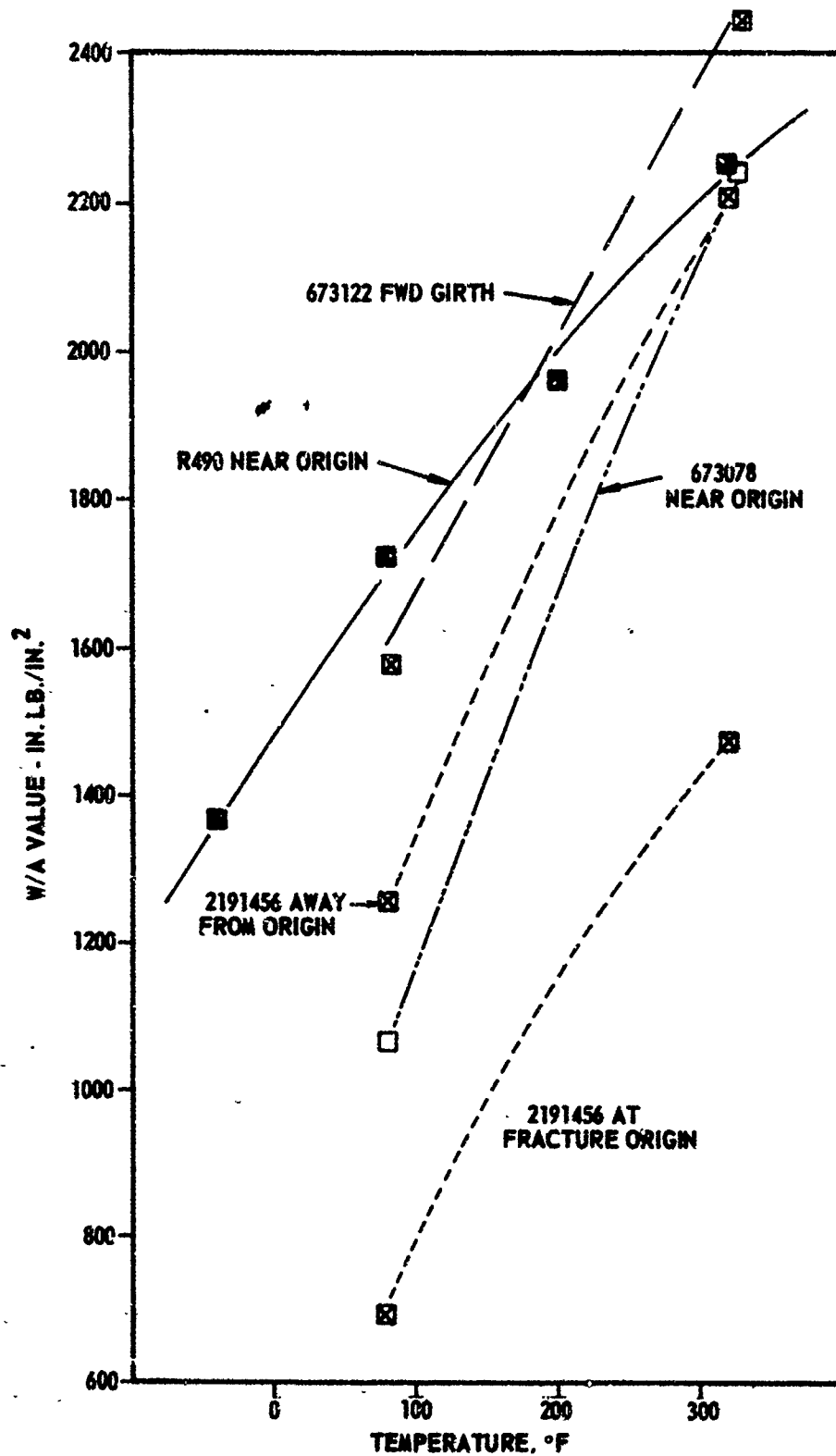


Figure 19. Precrack Charpy Impact Transition Curves for Welds in Minuteman Chambers

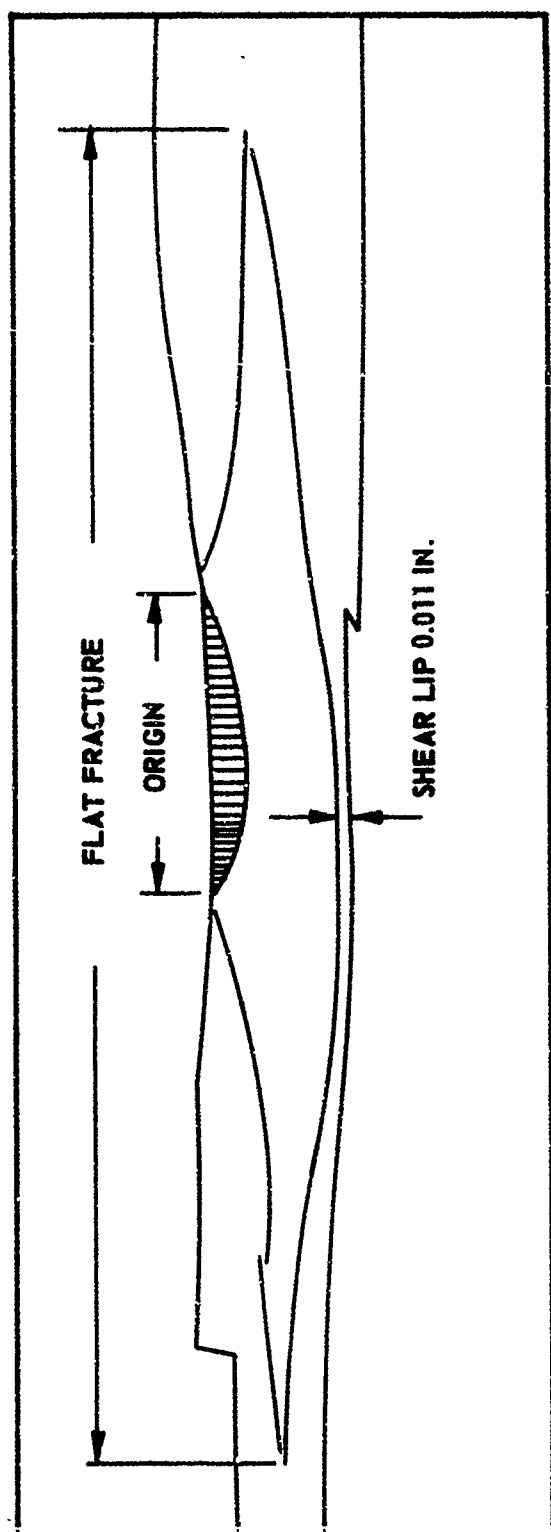


Figure 20. Fracture Origin in Chamber R512

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

fracture origin. Note that the flat-fracture region extended almost through the wall; the shear lip measured in the plane of the flat fracture was 0.011 in. wide at the OD surface of the chamber.

The following tabulation summarizes the W/A values for the 0.10-in.-thick body cylinders.

| Forward Cylinder | | Aft Cylinder | |
|-------------------|-------------------|-------------------|-------------------|
| Forward | Aft | Forward | Aft |
| 468 to 540 | 526 to 532 | 386 to 443 | 414 to 539 |
| Av (3) <u>509</u> | Av (3) <u>529</u> | Av (3) <u>414</u> | Av (3) <u>467</u> |

Note that the precrack Charpy impact test results obtained from the forward cylinder approximately 3 in. from the center girth weld were not significantly different from those from the opposite end of the cylinder. Furthermore, the aft cylinder had significantly lower toughness than the failure-origin cylinder.

h. Chamber R516

In October 1967, chamber R516 failed while at the 625-psig proof pressure (112-ksi hoop stress), 45 sec into the hold period. The fracture origin appeared to be in the aft cylinder, in the reinforced section of the center (G2) girth weld; the defect presumed to have initiated the failure was discolored and roughly semicircular, approximately 0.05 in. dia.

An estimate was made of the plane-strain (K_{Ic}) fracture toughness that was based on the measured crack dimensions

$$a = 0.05 \text{ in.}, 2c = 0.10 \text{ in.}, a/2c = 0.5$$

and the failure stress

$$F = 112 \text{ ksi}, F/F_{ty} = 112/163 = 0.69$$

the flaw-shape parameter and normalized crack depth were

$$Q = 2.3, a/Q = 0.022$$

which gave a plane-strain crack toughness from the chamber itself of

$$K_{Ic} = \underline{32 \text{ ksi-in.}^{1/2}}$$

This value is somewhat below the mean K_{Ic} value reported in Volume I for 109 forgings (two-sigma lower limit $35.8 \text{ ksi-in.}^{1/2}$).

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

The following tabulation summarizes the reinforced-section precrack Charpy impact data from chamber R516:

| <u>Forward Closure</u> | <u>Forward* Cylinder</u> | <u>Aft* Cylinder</u> | <u>Aft Closure</u> |
|----------------------------|------------------------------|--------------------------|------------------------|
| 356 to 428 | 328 to 405 | 389 to 457 | 320 to 381 |
| Av (3) <u>394</u> | Av (3) <u>358</u> | Av (3) <u>429</u> | Av (3) <u>355</u> |

Note that the precrack Charpy impact test results from the aft-cylinder reinforced section of the center girth weld were somewhat higher than those of the forward cylinder, but, in general there was little difference between the reinforced sections of various components in chamber R516.

1. Chamber R543

In December 1967, chamber R543 failed just after completing the 90-sec hold at the 627-psig proof pressure; failure occurred at 602 psig as the chamber was being depressurized. On the assumption that crack growth had become unstable just at the end of the 627-psig hold, the hoop stress at the onset of instability was 147 ksi. The fracture origin was in the aft cylinder, 18 in. forward of the aft (G3) girth weld. Examination of the metal in defect area revealed massive alpha in the microstructure and high interstitial content.

An estimate was made of the plane-strain (K_{Ic}) fracture toughness that was based on the flaw dimensions as measured in the fracture surface and the hoop fracture stress. In this chamber, the defect was not clearly defined. A void was observed in the ID surface near the center of the flat fracture identified as the fracture origin. The void was surrounded by massive alpha. This, then, constituted the lower bound of the initiating defect. The void was approximately 0.008 in. deep and 0.035 in. long.

$$a/2c = 0.23$$

$$F/F_{ty} = 147/163 = 0.90$$

$$Q = 1.23, a/Q = 0.0065$$

$$K_{Ic} = \underline{23 \text{ ksi-in.}^{1/2}}$$

*For the reinforced section at the center (G2) girth weld.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

which appears fictitiously low. The upper bound of defect dimension was determined by the distance between the shear lips at the ID surface ($2c = 0.25$ in.) and the depth of the faceted area surrounding the void ($a = 0.04$ in.).

$$a/2c = 0.17$$

$$F/2_{ty} = 147/163 = 0.90$$

$$Q = 1.07, a/Q = 0.037$$

$$K_{Ic} = \underline{55 \text{ ksi-in.}^{1/2}}$$

which appears fictitiously high when compared with the mean value reported in Volume I for 109 forgings. Thus, it appears that the effective flaw dimensions were somewhere between the bounds used in making the above calculations.

The following tabulation summarizes the W/A test results obtained in the 0.10-in.-thick walls of chamber R543:

| <u>Forward Closure</u> | <u>Forward Cylinder</u> | <u>Aft Cylinder</u> | <u>Aft Closure</u> |
|----------------------------|-----------------------------|-------------------------|------------------------|
| 448 to 504 | 351 to 500 | 336 to 371 | 491 to 583 |
| Av (3) <u>484</u> | Av (6) <u>446</u> | Av (5) <u>352</u> | Av (3) <u>554</u> |

Note that the precrack Charpy impact test results obtained from the aft cylinder (fracture origin) were somewhat lower than those obtained in the other components of the chamber.

j. Chamber 673078

In August 1963, chamber 673078 failed under rising load in a special proof test preliminary to hydroburst testing. Chamber 673078 constituted a special case because it contained overstrength components (ultimate tensile strength of the forward closure was 182.6 ksi and the forward cylinder was 183.5 ksi) and involved a weld cracking problem. The girth welds consisted of one fusion pass and two filler passes, with all welding done from the outside. The chamber survived the proof test as specified for 42-in.-dia Minuteman cases; viz, three cycles of 90 sec each at 1.1 (MEOP) maximum engine operating pressure (590 psig) with inhibited water. However, after the proof test, cracks were found on the inside-diameter surface at the root of the girth welds. Consequently, the welds were partially routed out and rewelded with two passes on the inside diameter. After welding, the chamber was again stress relieved and then subjected to three additional proof-test cycles to 590 psig. The welds were reported to be free of cracks.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

Because of the overstrength components, chamber 673078 was selected for hydroburst testing along with chambers 673095, 673147, and 674514.* However, because of a malfunctioning hydrotest rig (O-ring problems), the chamber was subjected to five additional cycles of pressurization, as summarized in the following tabulation:

| Cycle Number | Pressure, psig | Time, sec | |
|--------------|----------------|-----------|-------|
| | | Rise Time | Hold |
| 7(a) | 600 | 548 | 0 |
| 8 | 530 | 400 | 0 |
| 9 | 630 | 638 | 96 |
| | 720(b) | 328 | 0 |
| 10 | 620 | 616 | 120 |
| | 670(b) | 156 | 0 |
| 11 | 690 | 360 | Burst |

(a) Counting six prior proof-test cycles.

(b) Rising to burst pressure.

Thus, the chamber withstood a total of ten cycles of pressurization and then failed on the eleventh cycle after having been previously subjected to higher pressure and extended periods at sustained load. Although the chamber was not instrumented with breakwires, fracture appearance indicated the failure origin to be at the center girth weld, with the flat fracture predominantly on the forward-cylinder side of the weld. After the burst, X-ray inspection of the welds revealed general, excessive porosity and two transverse cracks in the reinforced section of the center girth weld approximately 180 degrees from the fracture origin. The two cracks, 2 in. apart, were approximately 1/8 in. long and extended from the weld fusion line into the heat-affected base metal. It was not reported whether the cracks were in the forward or aft barrel.

Part-through-crack (PTC) tensile tests of both the forward and aft body cylinders gave the following K_{Ic} values:

*As a preliminary to hydroburst testing, these chambers were to receive an additional proof test consisting of one cycle with a 90-sec hold at 640 psig; see Section IV,E,3,a.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

| <u>Chamber Component</u> | <u>PTC Tensile K_{Ic}, ksi-in.^{1/2}</u> |
|--------------------------|---|
| Forward Cylinder | 44.0 to 48.2 Av (6) <u>45.9</u> |
| Aft Cylinder | 39.3 to 43.0 Av (6) <u>40.8</u> |

Note that the measured K_{Ic} values for the forward cylinder were appreciably higher than the population mean of 39 ksi-in.^{1/2} (1.6 ksi-in.^{1/2} standard deviation) as determined for 109 forgings in Phase I; the K_{Ic} values for the aft cylinder, on the other hand, were in close agreement with the mean value.

The precrack Charpy impact data from the body cylinders on either side of the center girth weld together with data from the weld fusion zone are summarized in the following tabulation:

| <u>Forward Cylinder</u> | | <u>Weld Deposit*</u> | <u>Aft Cylinder</u> | |
|-------------------------|---------------------|----------------------|---------------------|--------------------|
| <u>Membr. Wall</u> | <u>Reinf. Sect.</u> | | <u>Reinf. Sect.</u> | <u>Membr. Wall</u> |
| 655 to 824 | 442 to 738 | 1005 to 1120 | 422 to 482 | 446 to 494 |
| Av (3) <u>727</u> | Av (3) <u>617</u> | Av (2) <u>1062</u> | Av (3) <u>456</u> | Av (3) <u>476</u> |

*Specimens from near the fracture origin

Note that the toughness of the forward cylinder was appreciably higher than that of the aft cylinder. Note, also, that the toughness of the weld was comparable to that of other chambers which were successfully hydroburst tested (see Section IV,E,2,d). If a crack had escaped detection in the lower toughness aft cylinder, a crack large enough to fail the chamber at 590 psig, it almost certainly would have popped-in and failed the chamber on the first excursion to pressure greater than 590 psig. If, on the other hand, the crack was in the higher-toughness, forward cylinder, the crack could have popped-in, been arrested and then by slow crack growth, subsequently come to a critical size under plane-stress conditions. This concept will be elaborated on in the following paragraphs.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

3. Discussion of the Leak-Before-Burst Crack-Arrest Concept

A graphical presentation of the leak-before-burst concept is shown in Figure 21. In establishing the curves of this figure, K_C was expressed in terms of precrack Charpy impact W/A values using the relationship established in Phase I; viz,

$$K_C = 10C(W/A) + 6700$$

In Figure 21, when the property data plot to the right of the line representing a given thickness, the material complies with the leak-before-burst criterion. With room-temperature precrack Charpy impact W/A values ranging from approximately 300 to 800 in.-lb/in.² (mean 480 in.-lb/in.²) and 0.2% offset yield strengths ranging from approximately 155 to 170 ksi in Minuteman 6Al-4V titanium, it is obvious that the leak-before-burst criterion that was based on yield-strength-magnitude working stresses cannot be met in Minuteman chambers. Thus, any flaw of stress intensity exceeding K_{IC} in either the membrane wall or the reinforced sections of the Minuteman chamber wall would be expected to burst the chamber during proof test. If, on the other hand, the leak-before-burst criterion were based on the actual hoop stress, the criterion might be met in some Minuteman chamber components.

Figure 22 shows the distribution of hoop stress in both 44- and 52-in.-dia Minuteman chambers at proof pressure. Figure 23 is a plot of hoop stress versus flaw dimension for a material with a yield strength of 165 ksi and a plane-strain crack toughness (K_{IC}) of 39 ksi-in.^{1/2} (three flaw shapes), and a plane-stress crack toughness of 300 in.-lb/in.² (36.7 ksi-in.^{1/2}), 500 in.-lb/in.² (56.7 ksi-in.^{1/2}) and 700 in.-lb/in.² (76.7 ksi-in.^{1/2}). For the plane-strain crack-toughness curves, the flaw dimension on the abscissa is surface-crack depth; the flaw shape is described by the ratio of crack depth to length ($a/2c$). The linear-elastic fracture-mechanics equation used in plotting the curves was

$$K_{IC}^2 = 1.21 \pi F^2 a/Q$$

as described by Tiffany*. The plane-strain crack toughness value of 39 ksi-in.^{1/2} used in plotting the curves was the mean value (1.6 ksi-in.^{1/2} standard deviation) obtained in Phase I from a study of 109 6Al-4V titanium Minuteman forgings. In plotting the plane-stress curves, the linear-elastic expression for a large, flat sheet containing a through crack was used

$$K_C^2 = \pi c_1 F^2$$

*ASTM Committee E-24, "Progress in the Measurement of Fracture Toughness and the Application of Fracture Mechanics to Engineering Problems," Materials Research and Standards Vol. 4(3), March 1964.

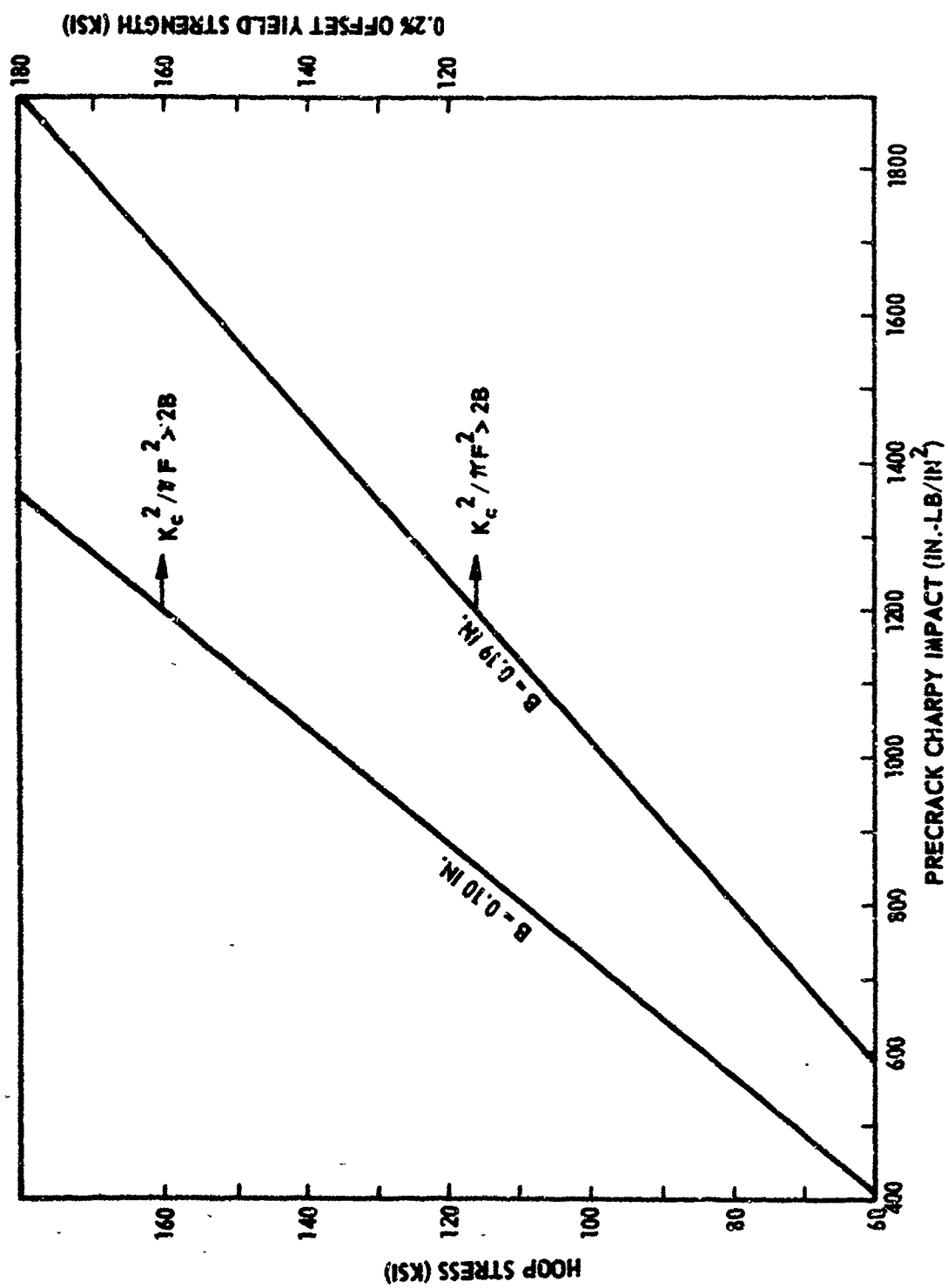


Figure 21. Leak-Before-Burst Criterion Limits for Minuteman 6Al-4V Titanium in Two Thicknesses

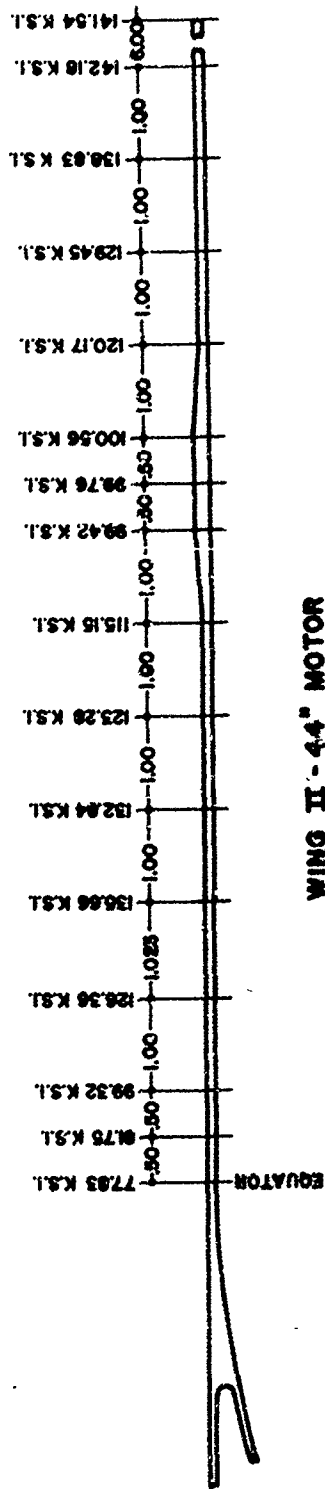
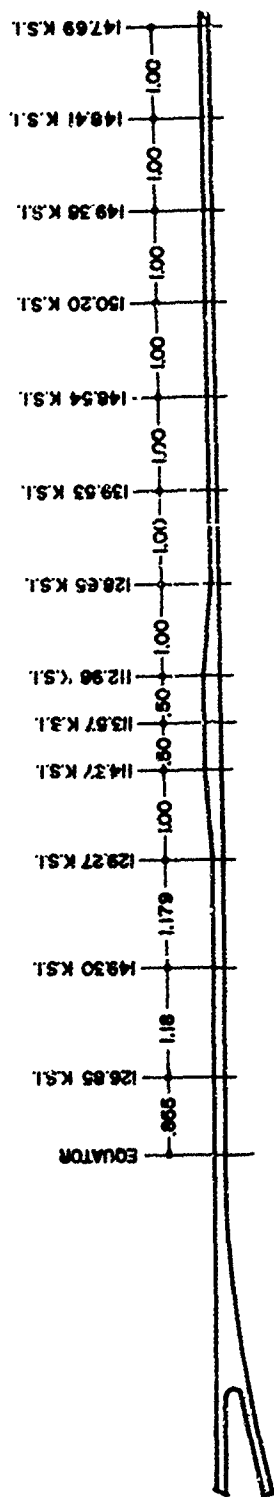


Figure 22. Distribution of Hoop Stress in 44- and 52-in.-dia Chambers at Proof Pressure

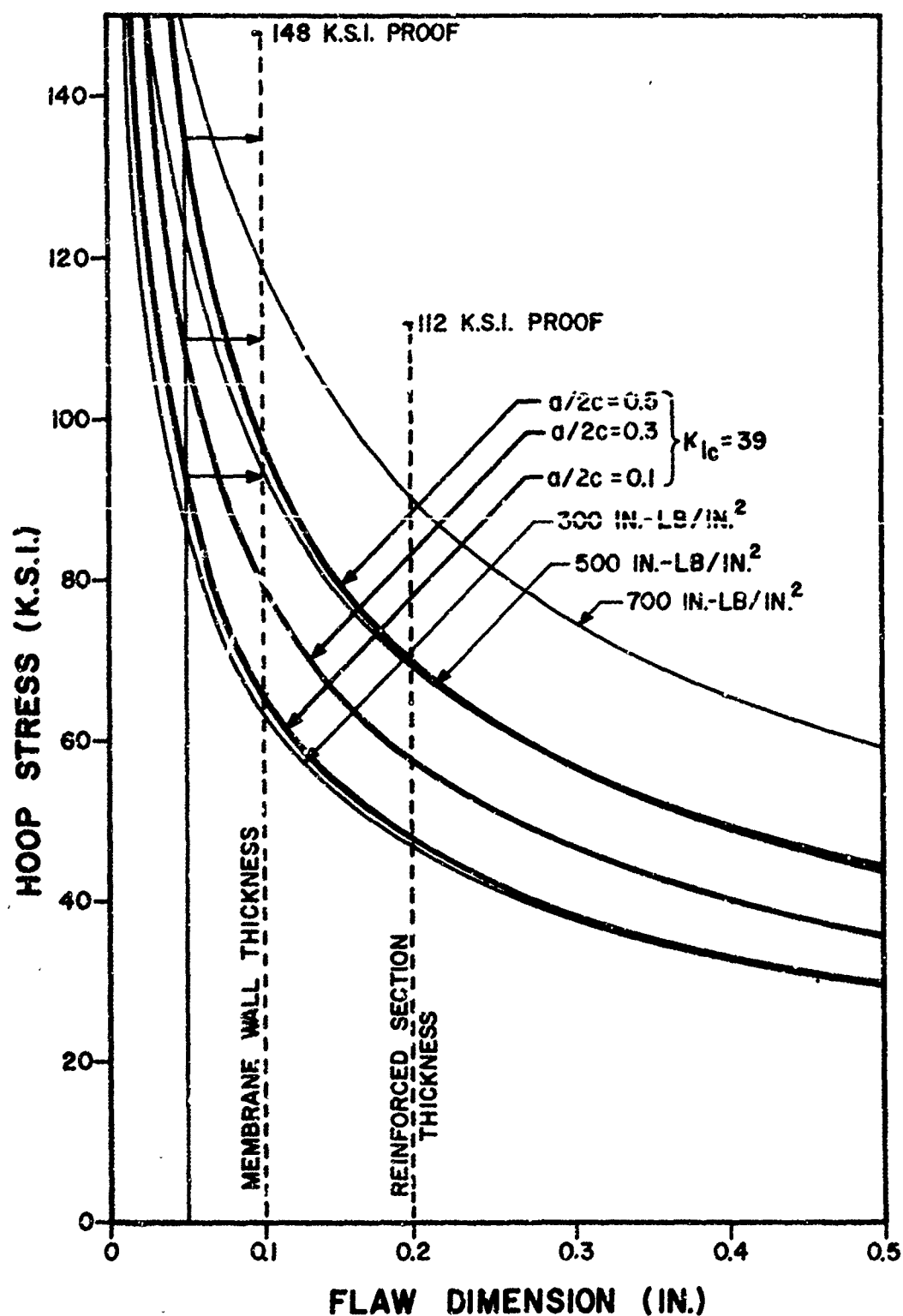


Figure 23. Hoop Fracture Stress as a Function of Flaw Dimension for Representative K_{Ic} and W/A Values in 6Al-4V Titanium at 165 ksi Yield Strength and 39 ksi-in. $1/2$ Plane-Strain Fracture Toughness

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

where c_1 is the effective half-length of the crack. Expressed in terms of the actual half-crack length and a plastic-zone correction

$$c_1 = c + K_c^2 / 2 \pi F_{ty}^2$$

Thus, for the plane-stress curves, the flaw dimension plotted on the abacissa is half-crack length. The plane-stress crack toughness values used in plotting the curves (300, 500, and 700 in.-lb/in.²) were generally representative of the range of W/A values measured in Minuteman chambers.

Consider now the interpretation of Figure 23 in terms of chamber performance. For example, with a semielliptical surface flaw 0.05 in. deep and 0.5 in. long ($a/2c = 0.1$) in the 0.10-in.-thick membrane wall, on pressurization, the flaw would pop-in due to plane-strain instability at approximately 93-ksi hoop stress (see arrow). If the plane-stress crack toughness is 300 in.-lb/in.² or less, there is no possibility of crack arrest and the chamber will fail catastrophically at pop-in. If, on the other hand, the same crack were in a material with markedly greater plane-stress crack toughness, say 700 in.-lb/in.², the pop-in could be arrested on reaching the biaxially stressed free surface at the chamber OD; i.e., the critical-crack half-length at this toughness level is greater than the wall thickness ($c > B$).

With a semielliptical surface flaw 0.05 in. deep and 0.15 in. long ($a/2c = 0.3$) in the 0.10-in.-thick membrane wall, on pressurization, the plane-strain pop-in would occur at approximately 110 ksi hoop stress. If the initial plane-strain instability (pop-in) nearly penetrated the wall thickness, in a material of low-to-intermediate plane-stress toughness, say 300 to 500 in.-lb/in.², it would propagate catastrophically to the complete failure of the chamber ($c < B$) without arrest. In a material with a plane-stress crack toughness of 700 in.-lb/in.², the crack would be arrested on penetrating the thickness but would fail the chamber, nevertheless, when the rising pressure brought the hoop stress to 119 ksi.

With a semicircular surface flaw 0.05 in. deep and 0.10 in. long ($a/2c = 0.5$) in the 0.10-in.-thick membrane wall, the chamber would almost reach proof pressure (148-ksi hoop stress) before plane-strain pop-in. However, if the pop-in instability enlarges the initial crack to a length approaching the thickness of the material and therefore, an effective length of approximately twice the material thickness, the plane-stress critical crack size will be exceeded and the chamber will fail ($c < B$) corresponding to 700 in.-lb/in.².

In the preceding examples, even if the crack size had been small enough so that the pop-in instability would not occur until the proof-pressure hoop stress was reached, fracture of the Minuteman second-stage

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

chamber would still have occurred, regardless of whether the flaw were in the membrane wall or in the reinforced section. This is readily seen by noting the relative position of the dashed material-thickness lines in Figure 23 and the 700 in.-lb/in.² crack toughness curve at the respective proof-pressure hoop stresses. For a material of $K_{IC} = 39 \text{ ksi-in.}^{1/2}$, it is of interest to note the maximum crack depths that can be tolerated in the reinforced section without plane-strain instability (pop-in) at proof pressure.

| Flaw Shape, <u>a/2c</u> | Maximum Crack Depth <u>112-ksi Hoop Stress</u> |
|----------------------------|---|
| 0.1 | 0.030 |
| 0.3 | 0.045 |
| 0.5 | 0.070 |

In the membrane wall where the hoop stress is higher, even smaller cracks would cause pop-in instability and fail the chamber.

Consider the case of chamber 673078 as a specific example. On the premise that the flaw initiating failure was only slightly larger than the 1/8-in.-long cracks discovered by X-ray, the initiating flaw in all probability fell within the following range:

Assuming a 0.13-in. Flaw Length

| | |
|-------------|---------------|
| a/2c = 0.1, | Depth = 0.013 |
| a/2c = 0.3, | Depth = 0.039 |
| a/2c = 0.5, | Depth = 0.065 |

With the defects in the reinforced section of the center girth weld, Figure 23 shows that multiple excursions to proof pressure (112 ksi hoop stress) in the reinforced section) would not be expected to cause pop-in of such a crack, assuming a K_{IC} of 39 ksi-in.^{1/2} or higher. Actually, PTC-tensile tests showed that the K_{IC} value in the forward cylinder was 46 ksi-in.^{1/2}. At 46 ksi-in.^{1/2}, the flaw dimensions tabulated above would have been smaller than the plane-strain critical crack size at the highest pressure (720 psig) seen by chamber 673078. The fact that the chamber withstood a total of ten cycles to proof pressure and then failed on the eleventh cycle after having been previously subjected to higher pressure and an extended period at sustained load, shows that there was slow crack growth in the chamber. When the initial flaw became a critical crack as a result of cycling and/or sustained load in a stress-corrosion-cracking environment, the pop-in instability further enlarged the crack to a depth approaching the material thickness and an effective length of approximately twice the thickness and consequently, the plane-stress critical crack dimension was exceeded and the chamber failed.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

Any question as to whether the initiating defect was in the forward or aft cylinder is resolved by the above observations. If either the defect that initiated fracture of the chamber or the cracks discovered by X-ray had been contained in the reinforced section of the lower-toughness aft cylinder, pop-in certainly would have occurred in the cycle to 720 psig and failed the chamber.

4. Summary of Premature Burst Findings

Table XV summarizes the correlation of fracture toughness and chamber performance for the premature bursts. Four chambers were omitted; viz, 2191456 and R490, because they were weld fusion zone failures, and chamber 673078 and R543 because of insufficient information about the flaw dimensions. The prediction of flaw criticality was based on Figure 23. Pop-in was predicted on the basis of an assumption of $K_{IC} = 39 \text{ ksi-in.}^{1/2}$, using the measured crack depth and shape. The prediction of failure stress was based on consideration of the relative positions of the curves relating stress and flaw size in Figure 23, and the premise that pop-in will not be arrested until it penetrates, or nearly penetrates, the wall thickness; therefore, after pop-in, the half-crack dimension that has to be arrested by plane-stress crack toughness corresponds to the wall thickness. Figure 24 illustrates a case of crack arrest in a PTC-tensile test of 6Al-4V titanium heat treated to 160-ksi yield strength*. Note the shear lip at the free surface opposite the part-through-crack pop-in. The clearly delineated band beyond the fatigue precrack is the limit of the pop-in. Apparently, the crack was arrested at this point, and then failed under plane-stress conditions when the load and crack length corresponded to K_C . The plane-strain and plane-stress crack toughness were calculated to be 41 and 100 $\text{ksi-in.}^{1/2}$, respectively.

Pop-in was predicted to occur either on or before reaching proof pressure in all chambers investigated except R516. When failure occurred after reaching proof pressure (under sustained load), the prediction of pop-in was inconsistent with chamber performance, assuming a plane-strain critical stress intensity of $39 \text{ ksi-in.}^{1/2}$. There were two such cases; however, both involved very short times at load (4 and 15 sec) before failure occurred. Thus, apparently a small amount of slow-crack growth was necessary to reach the critical crack dimension. In chamber R516, pop-in was not predicted on the basis of the defect size; the fact that failure occurred after 45 sec at proof pressure indicates that approximately 0.025 in. of slow crack growth occurred to make the initial 0.05-in. flaw critical. Again, this assumes a K_{IC} of $39 \text{ ksi-in.}^{1/2}$.

The prediction of failure stress as shown in Table XV was either close or conservative in four out of the six cases. In chamber R41,

*Gerberich, W. W., "A Discussion of Slow Crack Growth Associated with Plane-Strain Instability," Trans. Quarterly, Vol. 59(4), pp 899, December 1966.

TABLE IV

SUMMARY OF TOUGHNESS - CHAMBER PERFORMANCE CORRELATION

| Chamber S/N | Flaw Dimension | | Flaw Location | | W/A at Origin (in.-lb/in.) ² | Prediction of Flaw Criticality | | Failure Time (seconds) | Failure Hoop Stress | |
|----------------|---|------|---------------|--------------|---|-----------------------------------|--------|------------------------------|------------------------|-----------------|
| | a (in.) | a/2c | Component | Thick. (in.) | | Pop-in | Arrest | | Predicted (ksi) | Actual (ksi) |
| R26 | 0.10 | 0.56 | Fwd Clos | 0.19 | 426 (a) | Yes (b) | No | 15 (c) | 100 | 96 |
| R41 | 0.05 | 0.50 | Fwd Cyl | 0.10 | 550 | Yes | No | Loading (d) | 135 | 124 |
| 2191456 | Embedded flaw in deposited weld metal (see text) | | | | | | | | | |
| BL26 | 0.08 | 0.53 | Aft Adpt | 0.19 | 460 | Yes | No | 4 | 110 | 110 |
| R369 | 0.10 | 0.40 | Aft Cyl | 0.10 | 480 | Yes | No | Loading | 88 (e) | 80 |
| R490 | Failure originated in the deposited weld metal (see text) | | | | | | | | | |
| R512 | 0.03 | 0.15 | Fwd Cyl | 0.10 | 509 | Yes | No | Loading | 120 | 140 |
| R516 | 0.05 | 0.50 | Aft Cyl | 0.19 | 429 | No | No | 45 | 135 | 112 |
| R543 | Dimensions of defect uncertain (see text) | | | | | | | | | |
| | | | | | | | | 90+ | | |

(a) W/A measured in the 0.1-in.-thick membrane wall.

(b) The prediction of pop-in in each case was based on the assumption of $K_{Ic} = 39 \text{ ksi-in.}^{1/2}$.

(c) Time at proof pressure.

(d) Failure during rising load.

(e) No correction for deep flaw (see text).

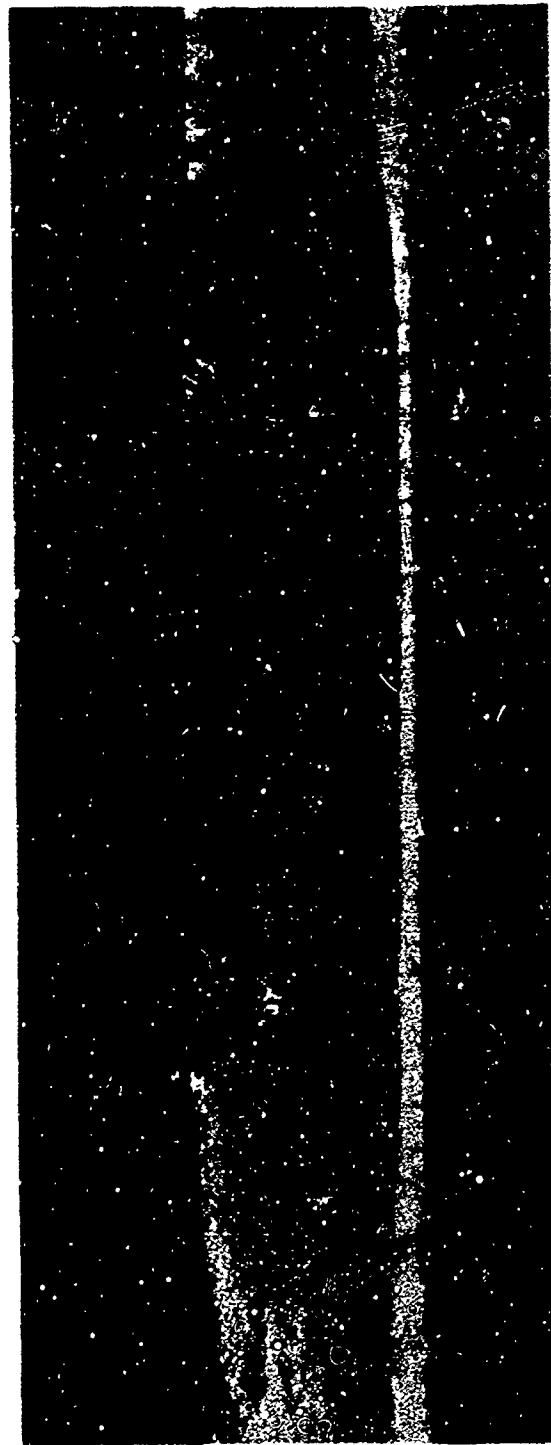
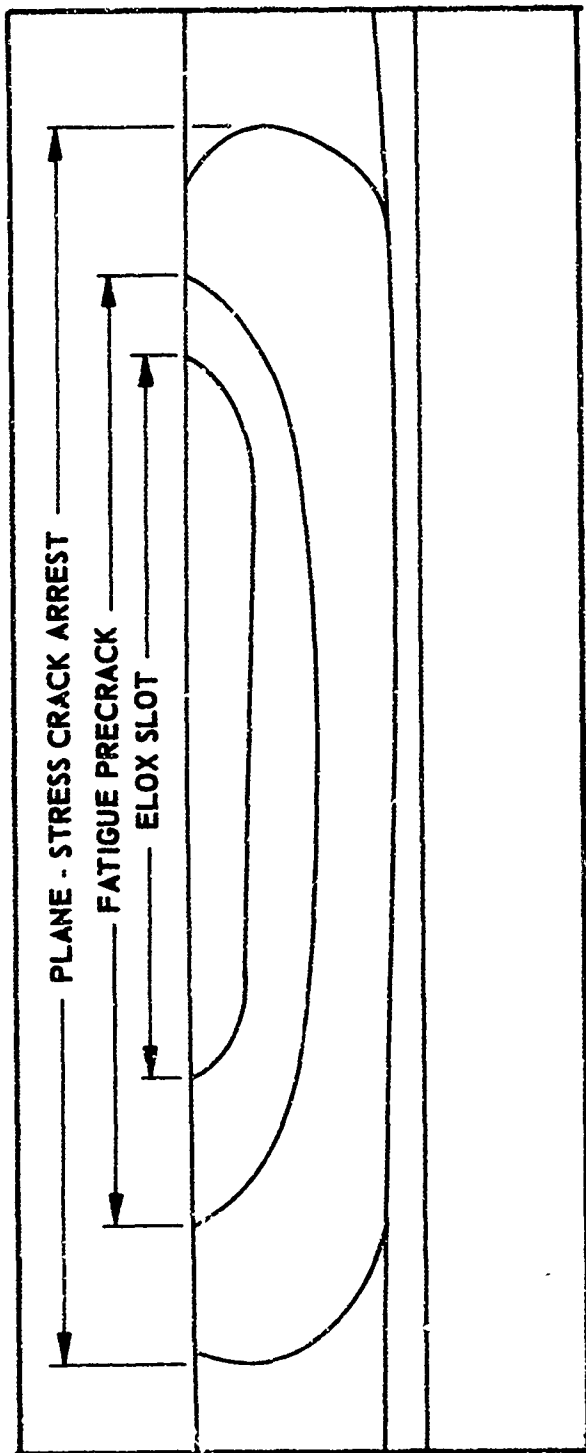


Figure 24. Plane-Stress Fracture Arrest in a PTC-Tensile Specimen of 1/8-in.-Thick 6Al-4V Titanium (160-ksi Yield Strength, 41 ksi-in.^{3/2} K_{Ic} and 100 ksi-in.^{1/2} K_{Ic})

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

the calculated plane-strain crack toughness (K_{IC}) was 36 ksi-in.^{1/2}, and, therefore, the use of Figure 23 which is based on $K_{IC} = 39$ ksi-in.^{1/2} would give a high prediction. Likewise, in chamber R516, the calculated value of plane-strain crack toughness ($K_{IC} = 32$ ksi-in.^{1/2}) was appreciably lower than the value used in plotting the curves of Figure 23 and, therefore, again would be expected to give a high prediction.

The prediction of no crack arrest that is based on the leak-before-burst criterion does not constitute a verification of the criterion because none of the forgings investigated (not even in the successfully hydroburst chambers discussed in subsequent paragraphs) had sufficient plane-stress crack toughness to arrest pop-in in either the reinforced section or the membrane wall. If an arrested pop-in produced a leak that could be readily detected and the proof cycle interrupted before reaching the critical stress intensity under plane-stress conditions, the leak-before-burst criterion would have practical significance for the Minuteman chamber. However, a leak-before-burst has never been reported in proof testing Minuteman chambers. If the plane-stress crack toughness of the 6Al-4V titanium used in the Minuteman could be increased to a minimum of value of approximately 900 in.-lb/in.² W/A in the membrane wall and approximately 800 in.-lb/in.² W/A in the reinforced section, any pop-in occurring at or below proof stress would produce a crack depth of less than the critical half-length under plane-stress conditions ($c > B$). The leak-before-burst criterion would then be of practical significance for Minuteman titanium. An alternative would be to increase the plane-strain (K_{IC}) crack toughness until the material could tolerate initial crack depths of much as the material thickness at proof stress; however, this would defeat the purpose of the proof test.

5. Successfully Hydroburst Chambers

Of the 14 Minuteman chambers selected for the data collection, two were successfully hydroburst tested at room temperature and two were successfully hydroburst tested at elevated temperature.

a. Room-Temperature Hydroburst Tests

Chambers 673078, 673095, 673147, and 674514 were selected for hydroburst testing as part of a qualification program originated by the Air Force Ballistic Systems Division (AFBSD) to evaluate motor cases with high-strength component sections (in excess of 180 ksi, ultimate tensile strength). Specific requirements were assigned to these discrepant chambers to prove the structural integrity of each unit. The first requirement was that the chambers be subjected to a hydrostatic proof-pressure test of one cycle with a 90-sec hold at 640 psig. The second requirement was that the

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

chambers be subjected to hydrostatic burst test, where the minimum burst pressure at room temperature would be 772 psig*, obtained as follows:

$$\begin{aligned}
 P_b (\text{Min}) &= \frac{\text{MEOP} \times \text{FS} \times t (\text{Max})}{K_{tu} (320^\circ\text{F}) \times t (\text{Min})} \\
 &= \frac{534 \times 1.15 \times 0.101}{0.835 \times 0.096} \\
 &= 772
 \end{aligned}$$

where MEOP = Maximum Expected Operating Pressure
= 534 psig at 320°F

FS = Design Minimum Factor of Safety
= 1.15

t (Max)/(Min) = design thickness range
= 0.101/0.096 in.

K_{tu} (320°F) = ultimate strength degradation factor at 320°F
= 0.835

It was specified that to be successful, the hydroburst tests would have to demonstrate considerable radial deformation preceding burst and have a factor of safety of 1.15 or higher, on the basis of the above minimum burst pressure.

The performance of chamber 673078 was discussed in the previous section because of its failure in proof test.

(1) Chamber 673147

On 12 March 1964, chamber 673147 was successfully burst tested in spite of component sections which exceeded the maximum acceptable tensile strength as defined by Minuteman design.

| Chamber Component | Ultimate Tensile Strength | |
|-------------------|---------------------------|---------|
| | Minimum | Average |
| Forward Cylinder | 181.1 | 181.9 |
| Aft Cylinder | 180.7 | 181.7 |

*This is a more severe requirement than usual. Minimum burst pressure at ambient temperature normally does not include the thickness ratio and is, therefore, only 737 psig.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

This chamber was subjected to a proof test of one cycle at 657 psig for 90 sec prior to burst*. No yielding was observed during the proof-pressure test. The chamber was then taken to burst; the burst pressure was 860 psig, 88 psig above the minimum acceptable burst pressure. Maximum radial deformation computed from strain data was 0.384 in. The factor of safety was 1.28. There was no evidence that the motor case was degraded by the presence of the "overstrength" components.

The ability of chamber 673147 to successfully withstand pressure up to 860 psig indicates that the chamber was virtually free of sizable defects. Moreover, although there was insufficient material to measure the toughness in the reinforced sections of the girth welds, the data obtained from the 0.1-in.-thick membrane sections in Phase I of this contract showed the toughness of the body cylinders to be as follows:

| <u>Component</u> | <u>Toughness, W/A (in.-lb/in.²)</u> | <u>Yield Strength, ksi</u> |
|------------------|--|--------------------------------|
| Forward Cylinder | 560 to 654 Av (6) <u>577</u> | <u>168.2</u> |
| Aft Cylinder | 498 to 663 Av (6) <u>547</u> | <u>168.6</u> |

Part-through-cracked (PTC) tensile tests of material from the forward and aft cylinders of chamber 673147 gave the following K_{Ic} values

| <u>Chamber Component</u> | <u>PTC-Tensile K_{Ic} (ksi-in.^{1/2}),</u> |
|--------------------------|---|
| Forward Cylinder | 31 to 44 Av (6) <u>40</u> |
| Aft Cylinder | 37 to 48 Av (6) <u>41</u> |

Note that these data were not significantly different from the population mean of 39 ksi-in.^{1/2} (1.6 ksi-in.^{1/2} standard deviation) as determined for 109 forgings in Phase I.

(2) Chamber 673095

On 18 September 1963, chamber 673095 was burst tested because it contained two components with ultimate tensile strength in excess of 180 ksi:

*Burst Test of a High-Strength Minuteman Wing II, Second-Stage Motor Case, Powell, R. H., Report 1091M-R, April 1964.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

| <u>Chamber</u> | <u>Ultimate Tensile Strength</u> | |
|------------------|----------------------------------|----------------|
| | <u>Minimum</u> | <u>Average</u> |
| Forward Dome | 180.4 | 181.2 |
| Forward Cylinder | 173.3 | 174.9 |
| Aft Cylinder | 183.5 | 183.8 |
| Aft Flange | 177.4 | 178.0 |

Prior to the room-temperature hydrotest, the chamber was subjected to one cycle of 640 psig for 60 sec followed by a second cycle of 640 psig for 70 sec (a total time of 130 sec at proof pressure). The chamber was then pressurized until it burst at 895 psig, 123 psig above the minimum acceptable burst pressure. This pressure represented an ultimate biaxial strength of

$$F_h = PR/t = 895 \times 22.13/0.099$$

$$= 200.1 \text{ ksi}$$

Deformation in the cylinder sections was recorded by strain gages. A maximum radial deformation of 0.689 in. was recorded in the forward cylinder near the origin of failure; the maximum radial deformation, at burst, in the aft cylinder was 0.335 in. The factor of safety was 1.33. Thus, there was no evidence that the motor was degraded by the presence of the overstrength components.

The precrack Charpy impact data from the membrane wall of this chamber, as determined in Phases I and II, are summarized in the following tabulation:

| <u>Chamber Component</u> | <u>Room-Temperature Precrack Charpy Impact, in.-lb/in.²</u> |
|--------------------------|--|
| Forward Closure | 476 to 613 Av (3) <u>529</u> |
| Forward Cylinder | 452 to 783 Av (12) <u>679*</u> |
| Aft Cylinder | 334 to 522 Av (10) <u>406*</u> |
| Aft Flange | 418 to 498 Av (3) <u>458</u> |

Note that the Charpy data showed the high-strength aft cylinder to have the lowest toughness; however, the high-strength forward closure had somewhat higher toughness than the lower-strength aft closure.

*Includes Phase I and Phase II data from both ends of the body cylinders.

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

The fact that the chamber withstood two excursions to proof pressure with a total of 130 sec at pressure, demonstrated that there were no defects in the chamber of critical size at 640-psig pressure. Likewise, the fact that the chamber went to 895 psig before it failed, with the failure origin in the forward cylinder, suggests that the lower-toughness aft cylinder was essentially free of defects.

(3) Chamber 674514

On 17 September 1963, chamber 674514 was burst tested because the forward dome was overstrength.

| Chamber Component | Ultimate Tensile Strength | |
|-------------------|---------------------------|--------------|
| | Minimum, ksi | Average, ksi |
| Forward Dome | 183.3 | 183.7 |
| Forward Cylinder | 174.9 | 177.1 |
| Aft Cylinder | 172.0 | 173.4 |
| Aft Flange | 173.9 | 174.9 |

Prior to the room-temperature hydrotest, the chamber was subjected to one cycle of 645 psig for 86 sec. The chamber was then pressurized until it burst at 898 psig, 126 psig above the minimum acceptable burst pressure. This pressure represented an ultimate biaxial strength of

$$\begin{aligned}F_h &= PR/t = 898 \times 22.13/0.098 \\&= 202.8 \text{ ksi}\end{aligned}$$

Deformation in the cylinders was recorded by strain gages. A maximum radial deformation of 0.367 in. was recorded in the forward cylinder; the maximum radial deformation in the aft cylinder was 0.336 in. The factor of safety was 1.34. Thus, there was no evidence that the motor was degraded by the presence of an overstrength component.

Rupture occurred longitudinally from the aft Y-joint through the forward Y-joint and through the forward dome. A second circumferential rip occurred in the aft barrel that extended approximately 330°. Although the origin of failure was not determined, the forward cylinder with the higher radial strain is suspect.

The precrack Charpy impact test data from the membrane wall of this chamber, as determined in Phases I and II are summarized in the following tabulation:

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

| <u>Chamber Component</u> | <u>Room Temperature Precrack Charpy Impact, in.-lb/in.²</u> |
|--------------------------|--|
| Forward Closure | 419 to 451 Av (3) <u>436</u> |
| Forward Cylinder | 364 to 496 Av (9) <u>418*</u> |
| Aft Cylinder | 302 to 396 Av (12) <u>344*</u> |
| Aft Flange | 317 to 531 Av (3) <u>448</u> |

*Includes Phase I and Phase II data from both ends of the body cylinders.

Note that the Charpy data from the high-strength forward closure were not appreciably different from those of the other components. The fact that the chamber went to 898 psig before it failed indicates that the chamber was essentially free of defects.

b. Elevated-Temperature Hydroburst Tests

(1) Chamber 673122

On 15 October 1962, chamber 673122 was externally heated to 321°F (average) by quartz lamps to simulate aerodynamic heating during flight. Rupture occurred at 713-psig pressure; break wires indicated the fracture origin to be near the center of the aft cylinder. The burst pressure exceeded the minimum allowable by approximately 4%.

The fracture propagated in a ductile manner (shear-type fracture) fore and aft in a relatively straight line from the origin in the aft cylinder, and terminated in the forward and aft domes.

The precrack Charpy impact data from the body cylinders of chamber 673122 as obtained in Phases I and II of this contract, as well as some data taken at the time of the hydroburst test, are summarized in the following tabulation:

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

The fact that the chamber withstood two excursions to proof pressure with a total of 130 sec at pressure, demonstrated that there were no defects in the chamber of critical size at 640-psig pressure. Likewise, the fact that the chamber went to 895 psig before it failed, with the failure origin in the forward cylinder, suggests that the lower-toughness aft cylinder was essentially free of defects.

(3) Chamber 674514

On 17 September 1963, chamber 674514 was burst tested because the forward dome was overstrength.

| Chamber Component | Ultimate Tensile Strength | |
|-------------------|---------------------------|--------------|
| | Minimum, ksi | Average, ksi |
| Forward Dome | 183.3 | 183.7 |
| Forward Cylinder | 174.9 | 177.1 |
| Aft Cylinder | 172.0 | 173.4 |
| Aft Flange | 173.9 | 174.9 |

Prior to the room-temperature hydrotest, the chamber was subjected to one cycle of 645 psig for 86 sec. The chamber was then pressurized until it burst at 898 psig, 126 psig above the minimum acceptable burst pressure. This pressure represented an ultimate biaxial strength of

$$\begin{aligned} F_h &= PR/t = 898 \times 22.13/0.099 \\ &= 202.8 \text{ ksi} \end{aligned}$$

Deformation in the cylinders was recorded by strain gages. A maximum radial deformation of 0.367 in. was recorded in the forward cylinder; the maximum radial deformation in the aft cylinder was 0.336 in. The factor of safety was 1.34. Thus, there was no evidence that the motor was degraded by the presence of an overstrength component.

Rupture occurred longitudinally from the aft Y-joint through the forward Y-joint and through the forward dome. A second circumferential rip occurred in the aft barrel that extended approximately 330°. Although the origin of failure was not determined, the forward cylinder with the higher radial strain is suspect.

The precrack Charpy impact test data from the membrane wall of this chamber, as determined in Phases I and II are summarized in the following tabulation:

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

| <u>Chamber Component</u> | <u>Room Temperature Precrack Charpy Impact, in.-lb/in.²</u> |
|--------------------------|--|
| Forward Closure | 419 to 451 Av (3) <u>436</u> |
| Forward Cylinder | 364 to 496 Av (9) <u>418*</u> |
| Aft Cylinder | 302 to 396 Av (12) <u>344*</u> |
| Aft Flange | 317 to 531 Av (3) <u>448</u> |

*Includes Phase I and Phase II data from both ends of the body cylinders.

Note that the Charpy data from the high-strength forward closure were not appreciably different from those of the other components. The fact that the chamber went to 898 psig before it failed indicates that the chamber was essentially free of defects.

b. Elevated-Temperature Hydroburst Tests

(1) Chamber 673122

On 15 October 1962, chamber 673122 was externally heated to 321°F (average) by quartz lamps to simulate aerodynamic heating during flight. Rupture occurred at 713-psig pressure; break wires indicated the fracture origin to be near the center of the aft cylinder. The burst pressure exceeded the minimum allowable by approximately 4%.

The fracture propagated in a ductile manner (shear-type fracture) fore and aft in a relatively straight line from the origin in the aft cylinder, and terminated in the forward and aft domes.

The precrack Charpy impact data from the body cylinders of chamber 673122 as obtained in Phases I and II of this contract, as well as some data taken at the time of the hydroburst test, are summarized in the following tabulation:

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

| Chamber Component | Precrack Charpy Impact Temperatures | | | |
|---------------------------|-------------------------------------|----------------------------------|---------------------------------|------------------------------------|
| | -40°F | RT | 200°F | 320°F |
| <u>Forward Cylinder</u> | 352 to 359 | 334 to 578 | 289 to 875 | 1080 to 1330 |
| <u>Reinforced Section</u> | Av (3) <u>355</u> | Av (6) <u>460</u> | Av (3) <u>638</u> | Av (3) <u>1167</u> |
| <u>Membrane Wall</u> | --- | 396 to 731 Av (19) <u>546</u> | 765 to 765 Av (2) <u>765</u> | <u>1170*</u> |
| <u>Aft Cylinder</u> | 378 to 464 | 387 to 634 | 719 to 865 | 1130 to 1300 |
| <u>Reinforced Section</u> | Av (3) <u>409</u> | Av (6) <u>560</u> | Av (3) <u>815</u> | Av (3) <u>1200</u> |
| <u>Membrane Wall</u> | --- | 441 to 672 Av (15) <u>525</u> | 723 to 908 Av (3) <u>801</u> | 1110 to 1315 Av (3) <u>1226</u> |

* One test.

Note that the body cylinders had approximately the same toughness

(2) Chamber 2192109

On 14 September 1964, chamber 2192109 was pressurized with preheated oil at 212°F (average) to simulate operating temperature. After a 570-psig hold for one minute without yielding, the chamber was pressurized until it ruptured at 728 psig. The origin of failure, as determined by break wire and accelerometer data, was located near the center of the aft barrel. The ultimate tensile stress for laboratory ambient temperature was calculated using the measured burst pressure, temperature and wall thickness near the origin of rupture.

$$F_{tu} = 177.0 \text{ ksi}$$

the factor of safety was 1.29.

The precrack Charpy impact data from the body cylinders of chamber 2192109 as obtained in Phases I and II are summarized in the following tabulation:

| Chamber Component | Precrack Charpy Impact Temperature | | | |
|---------------------------|------------------------------------|--------------------|-------------------|-------------------|
| | -40°F | RT | 200°F | 320°F |
| <u>Forward Cylinder</u> | | | | |
| <u>Reinforced Section</u> | 220 to 315 | 332 to 400 | 415 to 450 | 691 to 768 |
| 0.19 in. | Av (3) <u>279</u> | Av (2) <u>336</u> | Av (3) <u>438</u> | Av (3) <u>725</u> |
| <u>Membrane Wall</u> | --- | 242 to 454 | --- | --- |
| 0.10 in. | | Av (12) <u>364</u> | | |
| <u>Aft Cylinder</u> | | | | |
| <u>Membrane Wall</u> | --- | 339 to 423 | --- | --- |
| 0.10 in. | | Av (6) <u>381</u> | | |

IV, E, Correlation of Fracture Toughness and Chamber Performance (cont.)

Note that the room-temperature toughness in the membrane wall (fracture origin) was approximately the same in both body cylinders and appreciably lower than the mean (480 in.-lb/in.²). Note, also, that the toughness (438 in.-lb/in.²) of the forward cylinder at the temperature of hydroburst, 212°F, was appreciably lower than the mean (650 in.-lb/in.²) for that temperature. The fact that chamber 2192109 passed the proof test at room temperature indicates that the chamber was essentially free of defects.

SECTION V

SUMMARY AND CONCLUSIONS

A. SUMMARY

Material taken from second-stage 6Al-4V titanium Minuteman rocket motor cases was tested with precrack Charpy impact specimens to evaluate the following as factors affecting plane-stress crack toughness and/or chamber performance: (1) anisotropy and inhomogeneity, (2) forging practice, (3) interstitial-element chemistry, and (4) test temperature. The material was obtained from 14 hydroburst Minuteman chambers, nine of which were premature proof-test failures, four were successfully hydroburst chambers and one failed after 11 proof-test cycles. Closures, skirts and body cylinders from the 14 chambers provided data on 69 forgings involving three forging practices; viz, die, ring-roll, and extrusion. The small size of the precrack Charpy specimen permitted testing with the specimen oriented to propagate the crack in the chamber-axial direction, and with the specimen both in the 0.19-in.-thick reinforced section adjacent to the girth welds and in the 0.10-in.-thick walls on either side of the girth-weld reinforced sections. Selected forgings in each chamber were tested at -40, RT, 200, and 320°F. Particular attention was directed to the material in the immediate vicinity of fracture origins in an attempt to correlate fracture toughness and chamber performance.

1. Anisotropy and Inhomogeneity

Precrack Charpy specimens were cut to test crack propagation in the chamber-hoop and -axial directions. Marked anisotropy was noted in nine out of 13 body-cylinder forgings tested. Moreover, in four out of six components where secondary fracture occurred in the hoop direction, the W/A values in the hoop direction were either very low (as compared with a mean value of 477 in.-lb/in.²) or lower than those propagating fracture in the chamber-axial direction. Precrack Charpy specimens also were taken from both ends of many of the body cylinders to determine if there was a variation in toughness from end-to-end in a given cylinder forging. In some individual cylinders, there appeared to be a marked difference from end-to-end in both the membrane wall and the reinforced sections. However, analysis of variance indicated that there was no significant difference between the ends of the cylinders.

2. Effect of Chemistry and Forging Practice

Multiple covariance analysis showed that there were significant differences in the means for the different types of forgings when tests were made of the membrane-wall material. Moreover, multiple regression and correlation analysis indicated that for Minuteman chemistry carbon and oxygen were the interstitial-solid-solution elements having the greatest effect on toughness. Least-square best-fit equations also were obtained from the

V, A, Summary (cont.)

computer program relating interstitial content and W/A value. Analysis of variance to determine if there was a statistically significant difference between cylinder-forging W/A values showed a highly significant difference (significance level 0.0001). Also, it was found that there was a highly significant difference between W/A values obtained from the reinforced sections (specimens nominally 0.18 in. thick) and the membrane walls (specimens nominally 0.10 in. thick) of the cylinder forgings (significance level 0.0002).

3. Effect of Test Temperature

Marked temperature effects were observed in both precrack Charpy slow-bend and impact testing. The results indicated that testing for K_C at a single test temperature can be seriously misleading if service involves a range of temperature. In general, an increase in test temperature for Minuteman 6Al-4V titanium from -40 to 320°F resulted in a three-fold increase in plane-stress crack toughness; however, some heats are much less responsive to such a temperature increase than others. The forging-to-forging differences in response to test temperature makes testing of every forging necessary where toughness is a critical consideration.

4. Correlation of Toughness and Chamber Performance

Although there were marked differences in precrack Charpy impact W/A values from forging-to-forging in the Minuteman chambers, even the toughest of the forgings did not have sufficient plane-stress crack toughness to meet the leak-before-burst criterion. In one chamber (R369), which contained an initial flaw that very nearly penetrated the chamber wall, a calculation of the failure hoop stress that was based on the precrack Charpy W/A value and the measured crack length was in excellent agreement with the chamber hoop stress at the fracture origin. The measured W/A value was input to Irwin's flat-sheet analysis using the relationship established in Phase I between K_C and W/A; viz, $K_C = 100 (W/A) + 6700$.

The usefulness of a leak-before-burst criterion was evaluated on the basis of chamber hoop stress (rather than yield strength). Fracture surfaces in the vicinity of the initiating defects indicated that the flat fracture associated with pop-in usually extended nearly to the OD free surface. Thus, the plane-strain pop-in instability typically enlarges the initial crack to a depth approaching the thickness of the material and, therefore, to a length of approximately twice the thickness. Whether the initial pop-in instability will immediately fail the chamber (at the hoop stress existing at the instant of pop-in) or be arrested, requiring additional pressurization to fail the chamber, depends on the plane-stress critical crack size at the pop-in stress. If the plane-stress critical crack length is greater than twice the wall thickness ($c > B$), the pop-in will be arrested.

V, A, Summary (cont.)

Unfortunately, none of the components containing fracture origins had sufficient plane-stress crack toughness to arrest pop-in and, therefore, the usefulness of a leak-before-burst criterion that was based on hoop stress was not proven.

An attempt was made to predict the hoop stress at failure on the basis of the known flaw dimensions and the mean K_{IC} value as determined in Phase I from 109 forgings ($39 \text{ ksi-in.}^{1/2}$ with a standard deviation of $1.6 \text{ ksi-in.}^{1/2}$). The prediction was either close or conservative in four out of six cases. The calculated K_{IC} values that were based on the known hoop stress and the flaw dimensions in the discrepant cases were in one instance ($36 \text{ ksi-in.}^{1/2}$) within two-sigma standard deviation, while the other ($32 \text{ ksi-in.}^{1/2}$) was below the lower limit of a three-sigma standard deviation.

Four out of ten prematurely burst cases failed after the chamber was at proof pressure, and one failed on rising load after withstanding ten cycles of pressurization, including three cycles to higher pressure than the final burst pressure (chamber 673078). The latter was of particular interest because the flawed body cylinder had higher plane-strain crack toughness ($K_{IC} = 45.9 \text{ ksi-in.}^{1/2}$ as compared with a three-sigma upper limit of 43.8 that was based on the 109 forgings tested in Phase I) and higher-than-average W/A values (617 in.-lb/in.^2 in the reinforced sections and 727 in.-lb/in.^2 in the membrane wall). Thus, in five out of ten cases investigated, there was slow crack growth involved in the failure. The slow crack growth was very likely the result of cyclic loading in chamber 673078, and stress-corrosion cracking in the chambers which failed under sustained load (the proof-test environment was inhibited Los Angeles City water). One of the four chambers which failed after reaching proof pressure withstood the full 90 sec of sustained pressure, only to fail just after starting to unload. This case, therefore, had grown a crack during proof test that was just short of critical size at the end of the sustained-load portion of the proof test. If the crack had not continued to grow for a few seconds after starting to unload, the chamber would have passed the proof test while containing a near-critical crack.

B. CONCLUSIONS

1. Calculated values of plane-strain (K_{IC}) crack toughness were based on the measured initial-flaw size and the hoop stress causing fracture of full-scale second-stage 6Al-4V titanium Minuteman rocket motor cases were consistent with the plane-strain crack toughness measured in the 109 forgings tested in Phase I of the data collection.
2. The plane-stress (K_C) crack toughness in Minuteman-chemistry 6Al-4V titanium is not sufficient to meet Irwin's leak-before-burst criterion, nor is it sufficient to meet a leak-before-burst criterion that is based on

V, B, Conclusion (cont.)

the hoop stress at proof pressure. Thus, while a given defect subjected to rising load may be arrested after a plane-strain-instability pop-in, it will fail the chamber at or before reaching the Minuteman proof pressure because of insufficient plane-stress (K_c) crack toughness.

3. The precrack Charpy impact test is a useful method for estimating the K_c value in 6Al-4V Minuteman titanium on the basis of the relationship

$$K_c = 100 (W/A) + 6700$$

Precrack Charpy impact tests of 26 forgings gave a W/A sample mean of 477 in.-lb/in.² with a standard deviation of 140 in.-lb/in.². The two-sigma spread of 197 to 757 in.-lb/in.² was the result of large forging-to-forging differences in plane-stress crack toughness, which was in marked contrast to the two-sigma spread in plane-strain (K_{IC}) crack toughness, 35.8 to 42.2 ksi-in.^{1/2}, as measured in 109 forgings.

4. Statistically, there were highly significant differences in precrack Charpy impact W/A values between forgings and forging practices. The response of forgings to test temperature was variable; a rise in test temperature from -40 to 320°F produced a three-fold increase in W/A value in some forgings but only a slight increase in others. Thus, testing for plane-stress crack toughness at a single temperature can be seriously misleading where service involves a range of temperature. For critical service applications, every forging should be fracture tested and at temperatures encompassing the full range anticipated in service.

APPENDIX I
TABULATION OF DATA

TABLE XVI

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| <u>S/N</u> | <u>Minuteman Chamber Component</u> | <u>Specimen Location</u> | <u>Wall Thickness</u> | <u>RT</u> | | |
|------------|------------------------------------|--------------------------|-----------------------|---------------------------|--------------------------|----------------------------|
| | | | | <u>-40</u> | <u>200</u> | <u>320</u> |
| R26 | Dome | | 0.071 | | | |
| | | | | | 443 - 623 Avg(12) 494 | |
| | Fwd Adaptor | | 0.109 | 243 - 264 - Avg(3) 281 | 318 - 484 Avg(12) 426 | 469 - 505 Avg(3) 485 |
| | | | | | | 391 - 672 Avg(3) 519 |
| | Fwd Cyl | | 0.102 | 715 - 728 Avg(2) 722 | 691 - 906 Avg(4) 806 | 1039 - 1237 Avg(3) 1154 |
| | | | | | | 1223 - 1378 Avg(3) 1308 |
| | Aft Cyl | | 0.101 | 709 - 865 Avg(3) 791 | 663 - 815 Avg(2) 739 | 1052 - 1268 Avg(3) 1196 |
| | | | | | | 1254 - 1501 Avg(3) 1393 |
| | Aft Flange | | 0.107 | 580 - 668 Avg(3) 617 | 719 - 883 Avg(3) 822 | 916 - 1090 Avg(3) 1013 |
| | | | | | | 1387 - 1712 Avg(3) 1511 |

TABLE XVII

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER R26 (44 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|-----------------------|
| Forward Dome | A1 - 12 |
| Forward Adaptor | A13 - 24 |
| Forward Cylinder | |
| At G1 Weld | A25 - 36 [*] |
| At G2 Weld | - |
| Aft Cylinder | |
| At G2 Weld | A37 - 48* |
| At G3 Weld | - |
| Aft Flange | A49 - 60 |

*Location in the cylinder not known;
material taken adjacent to that used
in Phase I.

TABLE XVII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W-A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|-------|--------|--------|-----|--------|--------|---------|--------|------------|
| A-1 | 0.072 | 0.2567 | 0.0185 | 472 | 8.724 | 0.727 | 157.5 | 0.0708 | RT |
| A-2 | 0.071 | 0.2259 | 0.0160 | 486 | 7.776 | 0.648 | 158.6 | 0.1018 | RT |
| A-3 | 0.071 | 0.2486 | 0.0177 | 463 | 8.196 | 0.683 | 158.1 | 0.0562 | RT |
| A-4 | 0.071 | 0.2602 | 0.0185 | 540 | 9.996 | 0.833 | 156.2 | 0.0699 | RT |
| A-5 | 0.072 | 0.2459 | 0.0177 | 483 | 9.544 | 0.712 | 157.7 | 0.0806 | RT |
| A-6 | 0.074 | 0.2354 | 0.0174 | 456 | 7.932 | 0.661 | 158.4 | 0.0693 | RT |
| A-7 | 0.071 | 0.2554 | 0.0181 | 448 | 8.10 | 0.675 | 158.2 | 0.0704 | RT |
| A-8 | 0.071 | 0.2579 | 0.0183 | 443 | 8.10 | 0.675 | 158.2 | 0.0701 | RT |
| A-9 | 0.069 | 0.2393 | 0.0165 | 465 | 7.68 | 0.640 | 158.7 | 0.0869 | RT |
| A-10 | 0.070 | 0.2180 | 0.0153 | 524 | 8.016 | 0.668 | 158.3 | 0.0866 | RT |
| A-11 | 0.074 | 0.2366 | 0.0175 | 526 | 9.204 | 0.767 | 157.0 | 0.0620 | RT |
| A-12 | 0.074 | 0.2550 | 0.0189 | 623 | 11.772 | 0.981 | 154.5 | 0.0501 | RT |
| A-13 | 0.111 | 0.2532 | 0.0281 | 419 | 11.772 | 0.981 | 154.5 | 0.0504 | RT |
| A-14 | 0.119 | 0.2385 | 0.0284 | 410 | 11.652 | 0.971 | 154.6 | 0.0673 | RT |
| A-15 | 0.109 | 0.2598 | 0.0283 | 484 | 13.692 | 1.141 | 152.8 | 0.0677 | RT |
| A-16 | 0.116 | 0.2492 | 0.0289 | 446 | 12.876 | 1.073 | 153.5 | 0.0556 | RT |
| A-17 | 0.108 | 0.2390 | 0.0258 | 415 | 10.704 | 0.892 | 155.5 | 0.0773 | RT |
| A-18 | 0.110 | 0.2342 | 0.0258 | 443 | 11.436 | 0.953 | 154.8 | 0.0685 | RT |
| A-19 | 0.109 | 0.2279 | 0.0248 | 449 | 11.124 | 0.927 | 155.1 | 0.0752 | RT |
| A-20 | 0.109 | 0.2542 | 0.0277 | 437 | 12.108 | 1.004 | 154.2 | 0.0739 | RT |
| A-21 | 0.109 | 0.2285 | 0.0249 | 443 | 11.028 | 0.919 | 155.2 | 0.0772 | RT |

TABLE XVII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D. | Test Temp. |
|--------------|-------|--------|--------|------|--------|--------|---------|--------|------------|
| A-22 | 0.108 | 0.2521 | 0.0272 | 318 | 8.64 | 0.720 | 157.6 | 0.0687 | RT |
| A-23 | 0.109 | 0.1996 | 0.0218 | 445 | 9.696 | 0.808 | 156.5 | 0.1025 | RT |
| A-24 | 0.109 | 0.2528 | 0.0276 | 407 | 11.232 | 0.936 | 155.0 | 0.0736 | RT |
| A-25 | 0.101 | 0.2246 | 0.0227 | 691 | 15.696 | 1.308 | 151.1 | 0.0770 | RT |
| A-26 | 0.101 | 0.2649 | 0.0268 | 797 | 21.36 | 1.78 | 146.5 | 0.0641 | RT |
| A-27 | 0.102 | 0.2522 | 0.0257 | 906 | 23.28 | 1.94 | 145.2 | 0.0713 | RT |
| A-28 | 0.102 | 0.2465 | 0.0251 | 808 | 20.28 | 1.69 | 147.3 | 0.0822 | RT |
| A-29 | 0.102 | 0.2345 | 0.0239 | 728 | 17.40 | 1.45 | 149.7 | | -40°F |
| A-30 | 0.102 | 0.2620 | 0.0269 | 715 | 19.08 | 1.59 | 148.3 | | -40°F |
| A-31 | 0.102 | 0.2605 | 0.0266 | 1186 | 31.56 | 2.63 | 139.0 | | 200°F |
| A-32 | 0.102 | 0.2516 | 0.0257 | 1237 | 31.80 | 2.65 | 139.7 | | 200°F |
| A-33 | 0.102 | 0.2931 | 0.0299 | 1039 | 31.08 | 2.59 | 140.2 | | 200°F |
| A-34 | 0.102 | 0.2594 | 0.0265 | 1223 | 32.40 | 2.70 | 139.4 | | 320°F |
| A-35 | 0.102 | 0.2556 | 0.0261 | 1324 | 34.56 | 2.88 | 138.1 | | 320°F |
| A-36 | 0.102 | 0.2577 | 0.0263 | 1378 | 36.24 | 3.02 | 137.1 | | 320°F |
| A-37 | | | | | | | | | RT |
| A-38 | 0.102 | 0.2460 | 0.0251 | 663 | 16.644 | 1.387 | 150.3 | 0.0820 | RT |
| A-39 | 0.102 | 0.2539 | 0.0259 | 815 | 21.12 | 1.76 | 146.7 | 0.0510 | RT |
| A-40 | 0.102 | 0.2664 | 0.0272 | 799 | 21.72 | 1.81 | 146.3 | | -40°F |
| A-41 | 0.102 | 0.2634 | 0.0269 | 709 | 19.08 | 1.59 | 148.3 | | -40°F |
| A-42 | 0.101 | 0.2612 | 0.0264 | 865 | 22.80 | 1.90 | 145.5 | | -40°F |

TABLE XVII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|-------|--------|--------|------|--------|--------|---------|--------|------------|
| A-43 | 0.101 | 0.2485 | 0.0251 | 1267 | 31.80 | 2.65 | 139.7 | | 200°F |
| A-44 | 0.101 | 0.2624 | 0.0265 | 1268 | 33.60 | 2.80 | 138.7 | | 200°F |
| A-45 | 0.101 | 0.2654 | 0.0268 | 1052 | 28.20 | 2.35 | 142.0 | | 200°F |
| A-46 | 0.101 | 0.2488 | 0.0251 | 1501 | 37.68 | 3.14 | 136.3 | | 320°F |
| A-47 | 0.101 | 0.2422 | 0.0245 | 1254 | 30.72 | 2.56 | 140.4 | | 320°F |
| A-48 | 0.101 | 0.2505 | 0.0253 | 1423 | 36.00 | 3.00 | 137.3 | | 320°F |
| A-49 | 0.109 | 0.2639 | 0.0288 | 883 | 25.44 | 2.12 | 143.6 | 0.0647 | RT |
| A-50 | 0.109 | 0.2690 | 0.0293 | 864 | 25.32 | 2.11 | 143.7 | 0.0606 | RT |
| A-51 | 0.109 | 0.2637 | 0.0287 | 719 | 20.64 | 1.72 | 147.1 | 0.0635 | RT |
| A-52 | 0.109 | 0.2491 | 0.0272 | 604 | 16.416 | 1.368 | 150.5 | | -40°F |
| A-53 | 0.106 | 0.2413 | 0.0256 | 580 | 14.856 | 1.238 | 151.8 | | -40°F |
| A-54 | 0.106 | 0.2494 | 0.0264 | 668 | 17.64 | 1.47 | 149.5 | | -40°F |
| A-55 | 0.107 | 0.2415 | 0.0258 | 1033 | 26.64 | 2.22 | 143.0 | | 200°F |
| A-56 | 0.106 | 0.2569 | 0.0272 | 1090 | 29.64 | 2.47 | 141.1 | | 200°F |
| A-57 | 0.106 | 0.2471 | 0.0262 | 916 | 24.00 | 2.00 | 144.7 | | 200°F |
| A-58 | 0.108 | 0.2393 | 0.0258 | 1433 | 36.96 | 3.08 | 136.7 | | 320°F |
| A-59 | 0.106 | 0.2484 | 0.0263 | 1387 | 36.48 | 3.04 | 137.0 | | 320°F |
| A-60 | 0.106 | 0.2453 | 0.0260 | 1712 | 44.52 | 3.71 | 132.6 | | 320°F |
| A-61 | 0.104 | 0.239 | 0.0248 | 264 | 6.54 | 0.545 | 160.0 | 0.079 | -40°F |
| A-64 | 0.105 | 0.265 | 0.0278 | 257 | 7.25 | 0.596 | 159.5 | 0.053 | -40°F |
| A-67 | 0.104 | 0.256 | 0.0266 | 243 | 6.47 | 0.539 | 160.1 | 0.052 | -40°F |

TABLE XVII (cont.)

[illegible]

TABLE XVIII

PRECRACK CHARPY IMPACT DATA - 6Al-4V TITANIUM

| Minuteman #/N | Chamber Component | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|------------------|----------------------|----------------------|-------------------|----------------------|------------|-------------|
| | | | | -40 | RT | 320 |
| F41 | Dome | | 0.072 | 487 - 551 | 527 - 609 | 711 - 748 |
| | | | | Avg(3) 524 | Avg(3) 578 | Avg(3) 725 |
| | | | | | | 799 - 886 |
| | | | | | | Avg(3) 856 |
| | Fwd Adaptor | | 0.108 | 297 - 345 | 352 - 404 | 520 - 552 |
| | | | | Avg(3) 326 | Avg(3) 377 | Avg(3) 538 |
| | | | | | | 657 - 745 |
| | | | | | | Avg(3) 701 |
| | Fwd Cylinder | | 0.102 | 394 - 495 | 515 - 590 | 585 - 747 |
| | | | | Avg(3) 454 | Avg(3) 550 | Avg(3) 691 |
| | | | | | | 830 - 1054 |
| | | | | | | Avg(3) 952 |
| | Aft Cylinder | | 0.100 | 525 - 601 | 666 - 740 | 888 - 901 |
| | | | | Avg(3) 570 | Avg(3) 713 | Avg(3) 896 |
| | | | | | | 1184 - 1348 |
| | | | | | | Avg(2) 1266 |
| | Aft Flange | | 0.109 | 346 - 422 | 379 - 496 | 508 - 667 |
| | | | | Avg(3) 395 | Avg(3) 428 | Avg(3) 613 |
| | | | | | | 789 - 1049 |
| | | | | | | Avg(3) 908 |

TABLE XIX

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER R41 (44 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Dome | B1 - 12 |
| Forward Adaptor | B13 - 24 |
| Forward Cylinder | |
| At G1 Weld | B25 - 36* |
| At G2 Weld | - |
| Aft Cylinder | |
| At G2 Weld | B37 - 48* |
| At G3 Weld | - |
| Aft Flange | B49 - 60 |

*Location in the cylinder not known.

TABLE XIX (cont.)

| SPECIMEN NO | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C D | Test Temp. |
|-------------|-------|----------|--------|-----|----------|----------|---------|--------|------------|
| B-1 | 0.072 | 0.2581 | 0.0186 | 598 | 11.124 | 0.927 | 155.1 | 0.0541 | RT |
| B-2 | 0.072 | 0.2706 | 0.0195 | 609 | 11.88 | 0.990 | 154.4 | 0.0436 | RT |
| B-3 | 0.073 | 0.2498 | 0.0182 | 527 | 9.60 | 0.800 | 156.6 | 0.0614 | RT |
| B-4 | 0.072 | 0.2539 | 0.0183 | 487 | 8.916 | 0.743 | 157.3 | | -40°F |
| B-5 | 0.071 | 0.2594 | 0.0184 | 533 | 9.804 | 0.817 | 156.4 | | -40°F |
| B-6 | 0.071 | 0.2510 | 0.0178 | 551 | 9.804 | 0.817 | 156.4 | | -40°F |
| B-7 | 0.071 | 0.2616 | 0.0186 | 748 | 13.92 | 1.160 | 152.6 | | 200°F |
| B-8 | 0.071 | 0.2557 | 0.0182 | 711 | 12.444 | 1.037 | 153.9 | | 200°F |
| B-9 | 0.072 | 0.2686 | 0.0193 | 715 | 13.80 | 1.150 | 152.7 | | 200°F |
| B-10 | 0.071 | 0.2582 | 0.0183 | 884 | 16.176 | 1.348 | 150.7 | | 320°F |
| B-11 | 0.071 | 0.2538 | 0.0180 | 799 | 14.388 | 1.199 | 152.2 | | 320°F |
| B-12 | 0.073 | 0.2517 | 0.0184 | 886 | 16.296 | 1.358 | 150.6 | | 320°F |
| B-13 | 0.108 | 0.2481 | 0.0268 | 374 | 9.996 | 0.833 | 156.2 | 0.0576 | RT |
| B-14 | 0.109 | 0.2296 | 0.0250 | 352 | 8.808 | 0.734 | 157.4 | 0.0788 | RT |
| B-15 | 0.109 | 0.2250 | 0.0245 | 404 | 9.888 | 0.824 | 156.3 | 0.0836 | RT |
| B-16 | 0.109 | 0.2093 | 0.0228 | 337 | 7.680 | 0.640 | 158.7 | | -40°F |
| B-17 | 0.109 | 0.2160 | 0.0235 | 345 | 8.100 | 0.675 | 158.2 | | -40°F |
| B-18 | 0.108 | 0.2123 | 0.0229 | 297 | 6.804 | 0.567 | 159.7 | | -40°F |
| B-19 | 0.108 | 0.2520 | 0.0272 | 520 | 14.148 | 1.179 | 152.4 | | 200°F |
| B-20 | 0.108 | 0.2445 | 0.0264 | 700 | 18.48 | 1.54 | 148.8 | | 320°F |
| B-21 | 0.108 | 0.2491 | 0.0269 | 745 | 20.04 | 1.67 | 147.5 | | 320°F |

TABLE XIX (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|-------|----------|--------|------|--------|--------|---------|-----|------------|
| B-22 | 0.108 | 0.2639 | 0.0285 | 542 | 15.456 | 1.288 | 151.3 | | 200°F |
| B-23 | 0.107 | 0.2494 | 0.0267 | 552 | 14.748 | 1.229 | 151.9 | | 200°F |
| B-24 | 0.107 | 0.2436 | 0.0261 | 657 | 17.16 | 1.43 | 149.9 | | 320°F |
| B-25 | 0.104 | 0.2534 | 0.0264 | 545 | 14.388 | 1.199 | 152.2 | | RT |
| B-26 | 0.101 | 0.2478 | 0.0250 | 515 | 12.876 | 1.073 | 153.5 | | RT |
| B-27 | 0.101 | 0.2513 | 0.0254 | 590 | 14.976 | 1.248 | 151.7 | | RT |
| B-28 | 0.104 | 0.2412 | 0.0251 | 394 | 9.888 | 0.824 | 156.3 | | -40°F |
| B-29 | 0.101 | 0.2377 | 0.0240 | 495 | 11.88 | 0.990 | 154.4 | | -40°F |
| B-30 | 0.102 | 0.2263 | 0.0231 | 473 | 10.920 | 0.910 | 155.3 | | -40°F |
| B-31 | 0.101 | 0.2576 | 0.0260 | 585 | 15.216 | 1.268 | 151.5 | | 200°F |
| B-32 | 0.102 | 0.2271 | 0.0232 | 740 | 17.16 | 1.43 | 149.9 | | 200°F |
| B-33 | 0.101 | 0.2461 | 0.0249 | 747 | 18.60 | 1.55 | 148.7 | | 200°F |
| B-34 | 0.101 | 0.2282 | 0.0230 | 830 | 19.08 | 1.59 | 148.3 | | 320°F |
| B-35 | 0.103 | 0.2397 | 0.0247 | 1054 | 26.04 | 2.17 | 143.3 | | 320°F |
| B-36 | 0.101 | 0.2503 | 0.0253 | 972 | 24.60 | 2.05 | 144.3 | | 320°F |
| B-37 | 0.100 | 0.2479 | 0.0248 | 740 | 18.36 | 1.53 | 148.9 | | RT |
| B-38 | 0.100 | 0.2433 | 0.0243 | 666 | 16.176 | 1.348 | 150.7 | | RT |
| B-39 | 0.100 | 0.2515 | 0.0252 | 733 | 18.48 | 1.54 | 148.8 | | RT |
| B-40 | 0.100 | 0.2427 | 0.0243 | 601 | 14.616 | 1.218 | 152.0 | | -40°F |
| B-41 | 0.100 | 0.2541 | 0.0254 | 525 | 13.352 | 1.111 | 153.1 | | -40°F |
| B-42 | 0.100 | 0.2569 | 0.0257 | 583 | 14.976 | 1.248 | 151.7 | | -40°F |

TABLE XIX (cont.)

| SPECIMEN NO | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C D. | Test Temp. |
|----------------|-------|----------|--------|------|----------|----------|---------|------|---------------|
| B-43 | 0.100 | 0.2436 | 0.0244 | 900 | 21.96 | 1.83 | 142.1 | | 200°F |
| B-44 | 0.100 | 0.2541 | 0.0254 | 888 | 22.56 | 1.88 | 145.7 | | 200°F |
| B-45 | 0.100 | 0.2613 | 0.0261 | 901 | 23.52 | 1.96 | 145.0 | | 200°F |
| B-46 | 0.100 | 0.2517 | 0.0252 | 1348 | 33.96 | 2.83 | 138.5 | | 320°F |
| B-47 | 0.100 | 0.2299 | 0.0230 | 1184 | 27.24 | 2.27 | 142.6 | | 320°F |
| B-48 | | | | | | | | | |
| B-49 | 0.108 | 0.2266 | 0.0245 | 408 | 9.996 | 0.833 | 156.2 | | RT |
| B-50 | 0.109 | 0.2439 | 0.0266 | 379 | 10.092 | 0.841 | 156.1 | | RT |
| B-51 | 0.109 | 0.2553 | 0.0278 | 496 | 13.80 | 1.150 | 152.7 | | RT |
| B-52 | 0.111 | 0.2650 | 0.0294 | 416 | 12.228 | 1.019 | 154.1 | | -40°F |
| B-53 | 0.109 | 0.2438 | 0.0266 | 422 | 11.232 | 0.936 | 155.0 | | -40°F |
| B-54 | 0.108 | 0.2334 | 0.0252 | 346 | 8.724 | 0.727 | 157.5 | | -40°F |
| B-55 | 0.110 | 0.2621 | 0.0288 | 508 | 14.616 | 1.218 | 152.0 | | 200°F |
| B-56 | 0.110 | 0.2440 | 0.0268 | 663 | 17.76 | 1.48 | 149.4 | | 200°F |
| B-57 | 0.110 | 0.2518 | 0.0277 | 667 | 18.48 | 1.54 | 148.8 | | 200°F |
| B-58 | 0.109 | 0.2412 | 0.0263 | 1049 | 27.60 | 2.30 | 142.4 | | 320°F |
| B-59 | 0.109 | 0.2627 | 0.0286 | 789 | 22.56 | 1.88 | 145.7 | | 320°F |
| B-60 | 0.109 | 0.2632 | 0.0287 | 886 | 25.44 | 2.12 | 143.6 | | 320°F |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

TABLE IX

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| Mitsubishi Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|---------------------------|--|-------------------|-------------------------|-------------------------|---------------------------|
| | | | -40 | RT | 200 |
| BL26 | Fwd Closure 2-in. fwd of G1 weld | 0.114 | 370 - 421 Avg(2) 395 | 519 - 580 Avg(3) 554 | 724 - 775 Avg(3) 750 |
| | | | | | 973 - 1150 Avg(2) 1061 |
| | | | | | |
| Fwd | G1 reinforced section | 0.180 | | 405 - 432 Avg(2) 419 | |
| | | | | | |
| | | | | | |
| Fwd Cyl | G1 reinforced section | 0.180 | | 429 - 559 Avg(4) 486 | |
| | | | | | |
| | | | | | |
| Aft Cyl | 2-in. aft of G1 weld | 0.109 | | 433 - 482 Avg(4) 456 | |
| | | | | | |
| | | | | | |
| Aft Cyl | 2-in. fwd of G3 weld | 0.107 | 317 - 331 Avg(3) 326 | 441 - 438 Avg(3) 425 | 561 - 570 Avg(3) 564 |
| | | | | | 815 - 953 Avg(3) 864 |
| | | | | | |
| Aft closure | G3 reinforced section | 0.175 | | 418 - 541 Avg(4) 461 | |
| | | | | | |
| | | | | | |
| Aft closure | G3 reinforced section | 0.180 | | 380 - 623 Avg(4) 460 | |
| | | | | | |
| | | | | | |
| Aft closure | 2-in. aft of G3 weld | 0.114 | 393 - 450 Avg(3) 421 | 477 - 542 Avg(3) 518 | 637 - 715 Avg(3) 686 |
| | | | | | 965 - 1024 Avg(3) 989 |
| | | | | | |

TABLE XXI

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER BL-26 (44 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Dome | - |
| Forward Adaptor | D1 - 14 |
| Forward Cylinder | |
| At G1 Weld | D15 - 22 |
| At G2 Weld | - |
| Aft Cylinder | |
| At G2 Weld | - |
| At G3 Weld | D23 - 38 |
| Aft Flange | D39 - 54 |

TABLE XXI (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C D | Test Temp. |
|--------------|----------------|----------|--------|-----|----------|----------|---------|-------|------------|
| D-1 | 0.114 | 0.249 | 0.0284 | 370 | 10.50 | 0.875 | 155.7 | 0.071 | -40°F |
| D-5 | 0.115 | 0.280 | 0.0322 | 421 | 13.57 | 1.131 | 152.9 | 0.040 | -40°F |
| D-23 | 0.107 | 0.238 | 0.0255 | 331 | 8.45 | 0.704 | 157.8 | 0.080 | -40°F |
| D-27 | 0.107 | 0.271 | 0.0290 | 317 | 9.20 | 0.767 | 157.0 | 0.049 | -40°F |
| D-31 | 0.107 | 0.240 | 0.0257 | 329 | 8.45 | 0.704 | 157.8 | 0.060 | -40°F |
| D-43 | 0.114 | 0.280 | 0.0319 | 393 | 12.55 | 1.046 | 153.8 | 0.040 | -40°F |
| D-47 | 0.114 | 0.275 | 0.0314 | 421 | 13.21 | 1.101 | 153.2 | 0.046 | -40°F |
| D-51 | 0.115 | 0.283 | 0.0325 | 450 | 14.62 | 1.218 | 152.0 | 0.037 | -40°F |
| | | | | | | | | | |
| D-2 | 0.112 | 0.284 | 0.0318 | 562 | 17.88 | 1.49 | 149.3 | 0.037 | RT |
| D-6 | 0.114 | 0.285 | 0.0325 | 580 | 18.84 | 1.57 | 148.5 | 0.035 | RT |
| D-9 | 0.115 | 0.261 | 0.0300 | 519 | 15.58 | 1.298 | 151.2 | 0.059 | RT |
| D-11 | 0.196 0.181 | 0.316 | 0.0596 | 757 | 45.12 | 3.76 | 132.2 | - | RT |
| D-12 | 0.195 0.180 | 0.317 | 0.0594 | 741 | 44.04 | 3.67 | 132.8 | - | RT |
| D-13 | 0.195 0.178 | 0.274 | 0.0511 | 432 | 22.08 | 1.84 | 146.0 | 0.043 | RT |
| D-14 | 0.194 0.173 | 0.267 | 0.0477 | 405 | 19.32 | 1.61 | 148.2 | 0.043 | RT |
| D-15 | 0.190 0.176 | 0.257 | 0.0470 | 559 | 26.28 | 2.19 | 143.2 | 0.061 | RT |
| D-16 | 0.190 0.176 | 0.262 | 0.0479 | 514 | 24.60 | 2.05 | 144.3 | 0.056 | RT |
| D-17 | 0.190 0.175 | 0.254 | 0.0464 | 442 | 20.52 | 1.71 | 147.2 | 0.064 | RT |
| D-18 | 0.191 0.177 | 0.253 | 0.0467 | 420 | 20.04 | 1.67 | 147.8 | 0.063 | RT |
| D-19 | 0.109 | 0.266 | 0.0290 | 452 | 13.10 | 1.092 | 153.3 | 0.056 | RT |

TABLE XXI (cont.)

| SPECIMEN NO | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D. | Test Temp. |
|----------------|----------------|--------|--------|-----|--------|--------|---------|-------|---------------|
| D-20 | 0.109 | 0.280 | 0.0305 | 433 | 13.21 | 1.101 | 153.2 | 0.042 | RT |
| D-21 | 0.109 | 0.264 | 0.0288 | 455 | 13.10 | 1.092 | 153.3 | 0.057 | RT |
| D-22 | 0.109 | 0.276 | 0.0301 | 482 | 14.50 | 1.208 | 152.1 | 0.043 | RT |
| D-24 | 0.107 | 0.280 | 0.0300 | 411 | 12.34 | 1.028 | 154.0 | 0.039 | RT |
| D-28 | 0.107 | 0.271 | 0.0290 | 426 | 12.34 | 1.028 | 154.0 | 0.050 | RT |
| D-32 | 0.107 | 0.279 | 0.0299 | 438 | 13.10 | 1.092 | 153.3 | 0.042 | RT |
| D-35 | 0.185 0.166 | 0.272 | 0.0477 | 418 | 19.92 | 1.66 | 147.6 | 0.044 | RT |
| D-36 | 0.185 0.168 | 0.268 | 0.0473 | 454 | 21.48 | 1.79 | 146.5 | 0.048 | RT |
| D-37 | 0.185 0.168 | 0.270 | 0.0477 | 430 | 20.52 | 1.71 | 147.2 | 0.048 | RT |
| D-38 | 0.187 0.172 | 0.277 | 0.0497 | 541 | 26.88 | 2.24 | 142.9 | 0.041 | RT |
| D-39 | 0.187 0.176 | 0.238 | 0.0432 | 380 | 16.42 | 1.368 | 150.5 | 0.079 | RT |
| D-40 | 0.187 0.184 | 0.276 | 0.0512 | 623 | 31.92 | 2.66 | 139.7 | 0.041 | RT |
| D-41 | 0.187 0.177 | 0.263 | 0.0479 | 426 | 20.40 | 1.70 | 147.3 | 0.055 | RT |
| D-42 | 0.187 0.176 | 0.264 | 0.0479 | 411 | 19.68 | 1.64 | 147.8 | 0.052 | RT |
| D-44 | 0.114 | 0.283 | 0.0323 | 542 | 17.52 | 1.46 | 149.6 | 0.037 | RT |
| D-48 | 0.114 | 0.264 | 0.0301 | 534 | 16.06 | 1.338 | 150.8 | 0.056 | RT |
| D-52 | 0.114 | 0.275 | 0.0314 | 477 | 14.98 | 1.248 | 151.7 | 0.044 | RT |
| | | | | | | | | | |
| D-3 | 0.113 | 0.267 | 0.0302 | 775 | 23.40 | 1.95 | 145.1 | 0.052 | 200°F |
| D-7 | 0.114 | 0.271 | 0.0309 | 750 | 23.16 | 1.93 | 145.3 | 0.048 | 200°F |
| D-10 | 0.114 | 0.263 | 0.0300 | 724 | 21.72 | 1.81 | 146.3 | 0.059 | 200°F |

TABLE XXI (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|-------|--------|--------|------|--------|--------|---------|-------|------------|
| D-25 | 0.106 | 0.252 | 0.0267 | 570 | 15.22 | 1.268 | 151.5 | 0.069 | 200°F |
| D-29 | 0.106 | 0.264 | 0.0280 | 561 | 15.70 | 1.308 | 151.1 | 0.057 | 200°F |
| D-33 | 0.106 | 0.250 | 0.0265 | 561 | 14.86 | 1.238 | 151.8 | 0.070 | 200°F |
| D-45 | 0.113 | 0.270 | 0.0305 | 637 | 19.44 | 1.62 | 148.1 | 0.052 | 200°F |
| D-49 | 0.113 | 0.278 | 0.0314 | 715 | 22.44 | 1.87 | 145.8 | 0.044 | 200°F |
| D-53 | 0.113 | 0.271 | 0.0306 | 706 | 21.60 | 1.80 | 146.4 | 0.050 | 200°F |
| | | | | | | | | | |
| D-4 | 0.115 | 0.271 | 0.0312 | 973 | 30.36 | 2.53 | 140.7 | 0.051 | 320°F |
| D-8 | 0.115 | 0.271 | 0.0312 | 1150 | 35.88 | 2.99 | 137.4 | 0.050 | 320°F |
| D-26 | 0.107 | 0.264 | 0.0282 | 953 | 25.88 | 2.24 | 142.9 | 0.058 | 320°F |
| D-30 | 0.107 | 0.274 | 0.0293 | 823 | 24.12 | 2.01 | 144.5 | 0.045 | 320°F |
| D-34 | 0.107 | 0.265 | 0.0284 | 815 | 23.16 | 1.93 | 145.3 | 0.056 | 320°F |
| D-46 | 0.114 | 0.281 | 0.0320 | 1024 | 32.76 | 2.73 | 139.2 | 0.037 | 320°F |
| D-50 | 0.114 | 0.275 | 0.0314 | 978 | 30.72 | 2.56 | 140.4 | 0.046 | 320°F |
| D-54 | 0.114 | 0.278 | 0.0317 | 965 | 30.60 | 2.55 | 140.5 | 0.041 | 320°F |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

TABLE XXII

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| Minuteman Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|----------------------|-------------------|----------------------|------------|-------------|
| | | | -40 | Rt | 320 |
| 2191456 | Dome | 0.070 | 453 - 464 | 484 - 564 | 612 - 672 |
| | | | Avg(3) 458 | Avg(3) 530 | Avg(3) 648 |
| | Fwd Adaptor | 0.106 | 349 - 392 | 411 - 435 | 585 - 601 |
| | | | Avg(3) 367 | Avg(3) 423 | Avg(3) 592 |
| | Fwd Cyl | 0.100 | 380 - 402 | 418 - 537 | 593 - 637 |
| | | | Avg(3) 389 | Avg(3) 469 | Avg(3) 610 |
| | Aft Cyl | 0.101 | 618 - 693 | 767 - 768 | 1001 - 1063 |
| | | | Avg(3) 658 | Avg(3) 767 | Avg(3) 1038 |
| | Aft Flange | 0.107 | 532 - 576 | 638 - 725 | 864 - 935 |
| | | | Avg(3) 558 | Avg(3) 674 | Avg(3) 906 |
| | | | | | 1160 - 1258 |
| | | | | | Avg(3) 1194 |

(a) Adjacent to material tested in Phase I.

TABLE XXIII

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER 2191456 (44 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Dome | C1 - 12 |
| Forward Adaptor | C13 - 24 |
| Forward Cylinder | |
| At G1 Weld | C25 - 36* |
| At G2 Weld | - |
| Aft Cylinder | |
| At G2 Weld | C37 - 48* |
| At G3 Weld | - |
| Aft Flange | C49 - 60 |

*Location in the cylinder not known;
material taken adjacent to that used
in Phase I.

TABLE XXIII (cont.)

| SPECIMEN NO | WIDTH | DBN-cd | AREA | W A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|-------------|-------|--------|--------|-----|--------|--------|---------|-----|------------|
| C-1 | 0.069 | 0.2595 | 0.0179 | 564 | 10.092 | 0.841 | 156.1 | | RT |
| C-2 | 0.070 | 0.2597 | 0.0182 | 543 | 9.888 | 0.824 | 156.3 | | RT |
| C-3 | 0.072 | 0.2579 | 0.0186 | 484 | 9.000 | 0.750 | 157.2 | | RT |
| C-4 | 0.071 | 0.2569 | 0.0182 | 464 | 8.448 | 0.704 | 157.8 | | -40°F |
| C-5 | 0.069 | 0.2501 | 0.0173 | 453 | 7.836 | 0.653 | 158.5 | | -40°F |
| C-6 | 0.069 | 0.2540 | 0.0175 | 458 | 8.016 | 0.668 | 158.3 | | -40°F |
| C-7 | 0.069 | 0.2632 | 0.0182 | 672 | 12.228 | 1.019 | 154.1 | | 200°F |
| C-8 | 0.069 | 0.2416 | 0.0167 | 660 | 11.028 | 0.919 | 155.2 | | 200°F |
| C-9 | 0.069 | 0.2542 | 0.0175 | 612 | 10.704 | 0.892 | 155.5 | | 200°F |
| C-10 | 0.069 | 0.2515 | 0.0174 | 840 | 14.616 | 1.218 | 152.0 | | 320°F |
| C-11 | 0.069 | 0.2633 | 0.0182 | 915 | 16.644 | 1.387 | 150.3 | | 320°F |
| C-12 | 0.069 | 0.2611 | 0.0180 | 899 | 16.176 | 1.348 | 150.7 | | 320°F |
| C-13 | 0.106 | 0.2294 | 0.0243 | 411 | 9.996 | 0.833 | 156.2 | | RT |
| C-14 | 0.107 | 0.2554 | 0.0273 | 435 | 11.88 | 0.990 | 154.4 | | RT |
| C-15 | 0.107 | 0.2458 | 0.0263 | 423 | 11.124 | 0.927 | 155.1 | | RT |
| C-16 | 0.106 | 0.2605 | 0.0276 | 392 | 10.812 | 0.901 | 155.4 | | -40°F |
| C-17 | 0.106 | 0.2355 | 0.0250 | 349 | 8.724 | 0.727 | 157.5 | | -40°F |
| C-18 | 0.106 | 0.2426 | 0.0257 | 358 | 9.204 | 0.767 | 157.0 | | -40°F |
| C-19 | 0.106 | 0.2596 | 0.0275 | 601 | 16.536 | 1.378 | 150.4 | | 200°F |
| C-20 | 0.106 | 0.2434 | 0.0258 | 590 | 15.216 | 1.268 | 151.5 | | 200°F |
| C-21 | 0.105 | 0.2517 | 0.0264 | 585 | 15.456 | 1.288 | 151.3 | | 200°F |

TABLE XIII (cont.)

| SPECIMEN NO. | WIDTH | DBH - in. | AREA | W/A | in. - lb | ft - lb | DEGREES | C D | Test Temp. |
|--------------|-------|-----------|--------|-----|----------|---------|---------|-----|------------|
| C-22 | 0.105 | 0.2601 | 0.0273 | 848 | 23.16 | 1.93 | 145.3 | | 320°F |
| C-23 | 0.105 | 0.2563 | 0.0269 | 807 | 21.72 | 1.81 | 146.3 | | 320°F |
| C-24 | 0.105 | 0.2502 | 0.0263 | 725 | 19.08 | 1.59 | 148.3 | | 320°F |
| C-25 | 0.099 | 0.2415 | 0.0239 | 418 | 9.996 | 0.833 | 156.2 | | RT |
| C-26 | 0.099 | 0.2580 | 0.0255 | 537 | 13.692 | 1.141 | 152.8 | | RT |
| C-27 | 0.099 | 0.2319 | 0.0230 | 452 | 10.404 | 0.867 | 155.8 | | RT |
| C-28 | 0.099 | 0.2641 | 0.0261 | 402 | 10.500 | 0.875 | 155.7 | | -40°F |
| C-29 | 0.099 | 0.2535 | 0.0251 | 386 | 9.696 | 0.808 | 156.5 | | -40°F |
| C-30 | 0.099 | 0.2572 | 0.0255 | 380 | 9.696 | 0.808 | 156.5 | | -40°F |
| C-31 | 0.099 | 0.2233 | 0.0221 | 593 | 13.104 | 1.092 | 153.3 | | 200°F |
| C-32 | 0.099 | 0.2422 | 0.0240 | 600 | 14.388 | 1.199 | 152.2 | | 200°F |
| C-33 | 0.100 | 0.2370 | 0.0237 | 637 | 15.096 | 1.258 | 151.6 | | 200°F |
| C-34 | 0.100 | 0.2576 | 0.0258 | 977 | 25.20 | 2.10 | 143.8 | | 320°F |
| C-35 | 0.100 | 0.2416 | 0.0242 | 898 | 21.72 | 1.81 | 146.3 | | 320°F |
| C-36 | 0.100 | 0.2383 | 0.0238 | 842 | 20.04 | 1.67 | 147.5 | | 320°F |
| C-37 | 0.101 | 0.2526 | 0.0255 | 767 | 19.56 | 1.63 | 148.0 | | RT |
| C-38 | 0.101 | 0.2493 | 0.0252 | 767 | 19.32 | 1.61 | 148.2 | | RT |
| C-39 | 0.101 | 0.2448 | 0.0247 | 768 | 18.96 | 1.58 | 148.4 | | RT |
| C-40 | 0.103 | 0.2755 | 0.0284 | 663 | 18.84 | 1.57 | 148.5 | | -40°F |
| C-41 | 0.101 | 0.2482 | 0.0251 | 693 | 17.40 | 1.45 | 149.7 | | -40°F |
| C-42 | 0.101 | 0.2493 | 0.0252 | 618 | 15.576 | 1.298 | 151.2 | | -40°F |

TABLE XXIII (cont.)

| SPECIMEN NO | WIDTH | DBN - cd | AREA | W.A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|-------------|-------|----------|--------|------|--------|--------|---------|-----|------------|
| C-43 | 0.101 | 0.2563 | 0.0259 | 1001 | 25.92 | 2.16 | 143.4 | | 200°F |
| C-44 | 0.100 | 0.2627 | 0.0263 | 1063 | 27.96 | 2.33 | 142.2 | | 200°F |
| C-45 | 0.100 | 0.2502 | 0.0250 | 1051 | 26.28 | 2.19 | 143.2 | | 200°F |
| C-46 | 0.100 | 0.2648 | 0.0265 | 1331 | 35.28 | 2.94 | 137.7 | | 320°F |
| C-47 | 0.100 | 0.2614 | 0.0261 | 1246 | 32.52 | 2.71 | 139.3 | | 320°F |
| C-48 | 0.100 | 0.2678 | 0.0268 | 1482 | 39.72 | 3.31 | 135.2 | | 320°F |
| C-49 | 0.107 | 0.2441 | 0.0261 | 638 | 16.644 | 1.387 | 150.3 | | RT |
| C-50 | 0.106 | 0.2575 | 0.0273 | 725 | 19.80 | 1.65 | 147.7 | | RT |
| C-51 | 0.107 | 0.2568 | 0.0275 | 657 | 18.12 | 1.51 | 149.1 | | RT |
| C-52 | 0.108 | 0.2586 | 0.0279 | 532 | 14.856 | 1.238 | 151.8 | | -40°F |
| C-53 | 0.106 | 0.2579 | 0.0273 | 566 | 15.456 | 1.288 | 151.3 | | -40°F |
| C-54 | 0.108 | 0.2620 | 0.0283 | 576 | 16.296 | 1.358 | 150.6 | | -40°F |
| C-55 | 0.106 | 0.2571 | 0.0273 | 919 | 25.08 | 2.09 | 143.9 | | 200°F |
| C-56 | 0.107 | 0.2458 | 0.0263 | 935 | 24.60 | 2.05 | 144.3 | | 200°F |
| C-57 | 0.107 | 0.2440 | 0.0261 | 864 | 22.56 | 1.88 | 145.7 | | 200°F |
| C-58 | 0.108 | 0.2512 | 0.0271 | 1258 | 34.08 | 2.84 | 138.4 | | 320°F |
| C-59 | 0.107 | 0.2548 | 0.0273 | 1160 | 31.68 | 2.64 | 139.8 | | 320°F |
| C-60 | 0.108 | 0.2753 | 0.0297 | 1164 | 34.56 | 2.88 | 138.1 | | 320°F |
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TABLE XXIV

PRECRACK CHARPY IMPACT DATA - 6Al-4V TITANIUM

| Minuteman Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|----------------------|-------------------|----------------------|-------------------------|-------------------------|
| | | | -40 | RT | 200 |
| R369 | Fwd Skirt | 0.107 | | 615 - 636 Avg(3) 629 | 320 |
| | | | | 423 - 48 Avg(3) 446 | |
| | | | | 356 - 394 Avg(3) 374 | 471 - 486 Avg(3) 477 |
| | Fwd Closure | 0.116 | | | 659 - 806 Avg(3) 749 |
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| | Fwd Cyl | 0.190 | | | |
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| | Fwd Cyl | 0.185 | | | |
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| | Fwd Cyl | 0.107 | | | |
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| | Fwd Cyl | 0.108 | | | |
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| | Fwd Cyl | 0.185 | | | |
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| | Aft Cyl | 0.180 | | | |
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| | Aft Cyl | 0.104 | | | |
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| | Aft Cyl | 0.106 | | | |
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| | Aft Cyl | 0.180 | | | |
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| | Aft Cyl | 0.180 | | | |
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| | Aft Cyl | 0.180 | | | |
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TABLE XXIV (cont.)

| <u>Mitsubishi Chamber</u> <u>S/N</u> | <u>Specimen</u> <u>Location</u> | <u>Wall</u> <u>Thickness</u> | <u>Test Temperature, °F</u> | | |
|---|---|---------------------------------|-----------------------------|-------------------------|-------------------------|
| | | | <u>-40</u> | <u>RT</u> | <u>320</u> |
| R360 | Aft Closure G3 reinforced section | 0.190 | 297 - 335 Avg(3) 316 | 344 - 381 Avg(3) 366 | 512 - 548 Avg(3) 529 |
| | | | | | 728 - 829 Avg(3) 765 |
| | 3-in. aft of G3 weld | 0.114 | | 497 - 496 Avg(3) 492 | |
| | | | | | |
| | Aft Skirt | 0.117 | | 606 - 628 Avg(3) 615 | |
| | | | | | |

TABLE XXV

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER R369 (52 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Skirt | L1 - 3 |
| Forward Closure | L4 - 18 |
| Forward Cylinder | |
| At G1 Weld | L19 - 33 |
| At G2 Weld | L34 - 39 |
| Aft Cylinder | |
| At G3 Weld | L40 - 45 |
| At G3 Weld | L46 - 60 |
| Aft Closure | L61 - 75 |
| Aft Skirt | L76 - 78 |

TABLE XXV (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|----------------|--------|--------|-----|--------|--------|---------|-------|------------|
| L-7 | 0.193 0.186 | 0.315 | 0.0597 | 527 | 31.44 | 2.62 | 140.0 | | -40°F |
| L-11 | 0.194 0.188 | 0.315 | 0.0602 | 543 | 32.64 | 2.72 | 139.3 | | -40°F |
| L-15 | 0.194 0.188 | 0.316 | 0.0604 | 628 | 37.92 | 3.15 | 136.2 | | -40°F |
| L-19 | 0.191 0.182 | 0.314 | 0.0586 | 571 | 33.48 | 2.79 | 138.8 | | -40°F |
| L-23 | 0.189 0.176 | 0.242 | 0.0442 | 231 | 10.19 | 0.849 | 156.0 | 0.073 | -40°F |
| L-27 | 0.191 0.180 | 0.237 | 0.0440 | 205 | 9.00 | 0.750 | 157.2 | 0.080 | -40°F |
| L-49 | 0.189 0.175 | 0.240 | 0.0437 | 292 | 12.77 | 1.064 | 153.6 | 0.074 | -40°F |
| L-53 | 0.187 0.175 | 0.205 | 0.0371 | 280 | 10.40 | 0.867 | 155.8 | 0.111 | -40°F |
| L-57 | 0.188 0.178 | 0.207 | 0.0377 | 268 | 10.09 | 0.841 | 156.1 | 0.110 | -40°F |
| L-61 | 0.193 0.186 | 0.251 | 0.0476 | 315 | 14.98 | 1.248 | 151.7 | 0.065 | -40°F |
| L-65 | 0.193 0.186 | 0.240 | 0.0445 | 297 | 13.21 | 1.101 | 153.2 | 0.076 | -40°F |
| L-69 | 0.193 0.187 | 0.252 | 0.0479 | 335 | 16.06 | 1.338 | 150.8 | 0.065 | -40°F |
| | | | | | | | | | |
| L-1 | 0.107 | 0.258 | 0.0276 | 635 | 17.52 | 1.46 | 149.6 | 0.059 | RT |
| L-2 | 0.106 | 0.265 | 0.0281 | 636 | 17.88 | 1.49 | 149.3 | 0.050 | RT |
| L-3 | 0.107 | 0.255 | 0.0273 | 615 | 16.78 | 1.398 | 150.2 | 0.062 | RT |
| L-4 | 0.115 | 0.266 | 0.0306 | 486 | 14.86 | 1.238 | 151.8 | 0.053 | RT |
| L-5 | 0.116 | 0.258 | 0.0299 | 423 | 12.66 | 1.055 | 153.7 | 0.060 | RT |
| L-6 | 0.117 | 0.266 | 0.0309 | 428 | 13.21 | 1.101 | 153.2 | 0.049 | RT |
| L-8 | 0.194 0.188 | 0.253 | 0.0483 | 368 | 17.76 | 1.48 | 149.4 | 0.064 | RT |
| L-12 | 0.193 0.187 | 0.248 | 0.0471 | 356 | 16.78 | 1.398 | 150.2 | 0.070 | RT |

TABLE XXV (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | m. - lb | ft. - lb | DEGREES | C D | Test Temp. |
|--------------|----------------|----------|--------|-----------------|---------|----------|---------|-------|------------|
| L-16 | 0.193 0.188 | 0.255 | 0.0486 | 398 | 19.32 | 1.61 | 148.2 | 0.062 | RT |
| L-20 | 0.191 0.183 | 0.257 | 0.0481 | 297 | 14.27 | 1.189 | 152.3 | 0.059 | RT |
| L-24 | 0.189 0.179 | 0.243 | 0.0447 | 286 | 12.77 | 1.064 | 153.6 | 0.073 | RT |
| L-28 | 0.191 0.181 | 0.243 | 0.0452 | 303 | 13.69 | 1.141 | 152.8 | 0.074 | RT |
| L-31 | 0.107 | 0.259 | 0.0277 | 325 | 9.00 | 0.750 | 157.2 | 0.060 | RT |
| L-32 | 0.107 | 0.255 | 0.0273 | 330 | 9.00 | 0.750 | 157.2 | 0.061 | RT |
| L-33 | 0.107 | 0.252 | 0.0270 | 316 | 8.54 | 0.712 | 157.7 | 0.066 | RT |
| L-34 | 0.107 | 0.263 | 0.0281 | 349 | 9.80 | 0.817 | 156.4 | 0.055 | RT |
| L-35 | 0.108 | 0.252 | 0.0272 | 346 | 9.40 | 0.783 | 156.8 | 0.066 | RT |
| L-36 | 0.108 | 0.268 | 0.0289 | 332 | 9.60 | 0.800 | 156.6 | 0.048 | RT |
| L-37 | 0.190 0.183 | | | CRACKED THROUGH | | | | | |
| L-38 | 0.189 0.180 | 0.160 | 0.0295 | 207 | 6.12 | 0.510 | 160.5 | 0.156 | RT |
| L-39 | 0.188 0.177 | 0.239 | 0.0436 | 216 | 9.40 | 0.783 | 156.8 | 0.077 | RT |
| L-40 | 0.186 0.175 | 0.252 | 0.0455 | 377 | 17.16 | 1.43 | 149.9 | 0.064 | RT |
| L-41 | 0.187 0.174 | 0.247 | 0.0446 | 385 | 17.16 | 1.43 | 149.9 | 0.069 | RT |
| L-42 | 0.187 0.174 | 0.250 | 0.0451 | 359 | 16.18 | 1.348 | 150.7 | 0.067 | RT |
| L-43 | 0.104 | 0.261 | 0.0271 | 443 | 12.00 | 1.000 | 154.3 | 0.056 | RT |
| L-44 | 0.104 | 0.245 | 0.0255 | 432 | 11.02 | 0.919 | 155.2 | 0.073 | RT |
| L-45 | 0.104 | 0.260 | 0.0270 | 489 | 13.21 | 1.101 | 153.2 | 0.057 | RT |
| L-46 | 0.106 | 0.255 | 0.0270 | 485 | 13.10 | 1.092 | 153.3 | 0.062 | RT |
| L-47 | 0.106 | 0.258 | 0.0273 | 472 | 12.88 | 1.073 | 153.5 | 0.060 | RT |

TABLE XXV (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|----------------|--------|--------|-----|--------|--------|---------|-------|------------|
| L-48 | 0.106 | 0.264 | 0.0280 | 514 | 14.39 | 1.109 | 152.2 | 0.052 | RT |
| L-50 | 0.189 0.176 | 0.206 | 0.0376 | 376 | 14.15 | 1.179 | 152.4 | 0.111 | RT |
| L-54 | 0.188 0.176 | 0.222 | 0.0404 | 377 | 15.22 | 1.268 | 151.5 | 0.094 | RT |
| L-58 | 0.188 0.175 | 0.225 | 0.0408 | 350 | 14.27 | 1.189 | 152.3 | 0.089 | RT |
| L-62 | 0.193 0.185 | 0.216 | 0.0408 | 344 | 14.04 | 1.170 | 152.5 | 0.101 | RT |
| L-66 | 0.193 0.185 | 0.248 | 0.0469 | 381 | 17.88 | 1.49 | 149.3 | 0.069 | RT |
| L-70 | 0.193 0.187 | 0.205 | 0.0390 | 372 | 14.50 | 1.208 | 152.1 | 0.111 | RT |
| L-73 | 0.114 | 0.263 | 0.0300 | 487 | 14.62 | 1.218 | 152.0 | 0.055 | RT |
| L-74 | 0.114 | 0.265 | 0.0302 | 492 | 14.86 | 1.238 | 151.8 | 0.053 | RT |
| L-75 | 0.114 | 0.265 | 0.0302 | 496 | 14.98 | 1.248 | 151.7 | 0.052 | RT |
| L-76 | 0.117 | 0.271 | 0.0317 | 628 | 19.92 | 1.66 | 147.6 | 0.090 | RT |
| L-77 | 0.117 | 0.261 | 0.0305 | 610 | 18.60 | 1.55 | 148.7 | 0.052 | RT |
| L-78 | 0.117 | 0.264 | 0.0309 | 606 | 18.72 | 1.56 | 148.6 | 0.054 | RT |
| | | | | | | | | | |
| L-9 | 0.193 0.186 | 0.249 | 0.0472 | 473 | 22.32 | 1.86 | 145.9 | 0.068 | 200°F |
| L-13 | 0.194 0.184 | 0.255 | 0.0482 | 471 | 22.68 | 1.89 | 145.6 | 0.061 | 200°F |
| L-17 | 0.193 0.187 | 0.251 | 0.0477 | 486 | 23.16 | 1.93 | 145.3 | 0.066 | 200°F |
| L-21 | 0.190 0.181 | 0.229 | 0.0425 | 404 | 17.16 | 1.43 | 149.9 | 0.088 | 200°F |
| L-25 | 0.190 0.180 | 0.191 | 0.0353 | 343 | 12.11 | 1.009 | 154.2 | 0.125 | 200°F |
| L-29 | 0.192 0.182 | 0.251 | 0.0469 | 409 | 19.20 | 1.60 | 148.3 | 0.065 | 200°F |
| L-51 | 0.194 0.174 | 0.269 | 0.0495 | 599 | 29.64 | 2.47 | 141.1 | 0.048 | 200°F |

TABLE XXV (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|----------------|--------|--------|-----|--------|--------|---------|-------|------------|
| L-55 | 0.188 0.176 | 0.229 | 0.0417 | 506 | 21.12 | 1.76 | 146.7 | 0.085 | 200°F |
| L-59 | 0.188 0.174 | 0.228 | 0.0413 | 465 | 19.20 | 1.60 | 148.3 | 0.087 | 200°F |
| L-63 | 0.193 0.186 | 0.249 | 0.0472 | 526 | 24.84 | 2.07 | 144.1 | 0.068 | 200°F |
| L-67 | 0.193 0.183 | 0.248 | 0.0466 | 512 | 23.88 | 1.99 | 144.8 | 0.068 | 200°F |
| L-71 | 0.192 0.182 | 0.249 | 0.0471 | 548 | 25.80 | 2.15 | 143.5 | 0.069 | 200°F |
| | | | | | | | | | |
| L-10 | 0.194 0.188 | 0.263 | 0.0502 | 782 | 39.24 | 3.27 | 135.4 | 0.055 | 320°F |
| L-14 | 0.194 0.188 | 0.231 | 0.0441 | 650 | 29.04 | 2.42 | 141.5 | 0.083 | 320°F |
| L-18 | 0.193 0.187 | 0.250 | 0.0475 | 806 | 38.28 | 3.19 | 136.0 | 0.065 | 320°F |
| L-22 | 0.190 0.179 | 0.202 | 0.0373 | 550 | 20.52 | 1.71 | 147.2 | 0.115 | 320°F |
| L-26 | 0.192 0.184 | 0.237 | 0.0446 | 557 | 24.84 | 2.07 | 144.1 | 0.080 | 320°F |
| L-30 | 0.192 0.185 | 0.240 | 0.0452 | 568 | 25.68 | 2.14 | 143.6 | 0.078 | 320°F |
| L-52 | 0.188 0.176 | 0.251 | 0.0457 | 804 | 36.72 | 3.06 | 136.9 | 0.064 | 320°F |
| L-56 | 0.188 0.176 | 0.247 | 0.0450 | 869 | 39.12 | 3.26 | 135.5 | 0.067 | 320°F |
| L-60 | 0.189 0.177 | 0.248 | 0.0454 | 756 | 34.32 | 2.86 | 139.3 | 0.066 | 320°F |
| L-64 | 0.193 0.187 | 0.252 | 0.0479 | 829 | 39.72 | 3.31 | 135.2 | 0.066 | 320°F |
| L-68 | 0.192 0.185 | 0.236 | 0.0445 | 728 | 32.40 | 2.70 | 139.4 | 0.082 | 320°F |
| L-72 | 0.193 0.187 | 0.247 | 0.0469 | 739 | 34.68 | 2.89 | 138.1 | 0.073 | 320°F |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

TABLE XXVI

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| Minuteman Chamber S/N | Component | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|-----------|--------------------------|-------------------|----------------------------|----------------------------|----------------------------|
| | | | | -40 | RT | 200 |
| R490 | Fwd Skirt | | 0.108 | | 471 - 570 Avg(3) 516 | 320 |
| | | 3-in. fwd of G1 weld | 0.114 | | 367 - 387 Avg(3) 376 | |
| | | G1 reinforced section | 0.178 | 270 - 296 Avg(3) 284 | 350 - 436 Avg(3) 388 | 636 - 780 Avg(3) 706 |
| | Fwd Cyl | G1 reinforced section | 0.180 | | 346 - 421 Avg(3) 378 | |
| | | 3-in. aft of G1 weld | 0.107 | | 343 - 435 Avg(3) 393 | |
| | | 3-in. fwd of G2 weld | 0.109 | | 321 - 466 Avg(3) 410 | |
| | | ditto hoop | 0.109 | | 654 - 703 Avg(3) 680 | |
| | | G2 reinforced section | 0.182 | 237 - 267 Avg(3) 256 | 323 - 366 Avg(3) 347 | 556 - 706 Avg(3) 644 |
| | | G2 reinforced section | 0.185 | | 315 - 380 Avg(3) 343 | 636 - 668 Avg(3) 656 |
| Aft Cyl | | G2 weld (hoop) | 0.195 | 1250 - 1530 Avg(3) 1363 | 1656 - 1836 Avg(3) 1721 | 2160 - 2320 Avg(3) 2253 |
| | | 3-in. aft of G2 weld | 0.109 | | 379 - 388 Avg(3) 382 | |
| | | ditto hoop | 0.110 | | 403 - 439 Avg(3) 426 | |

TABLE XXVI (cont.)

| Minuteman Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|------------------------|--------------------------|----------------------|-------------------------|-------------------------|
| | | | -40 | RT | 320 |
| R490 | Aft Cyl (continued) | 3-in. fwd of G3 weld | 0.107 | 256 - 311 Avg(3) 284 | |
| | | | | 260 - 303 Avg(3) 289 | |
| | Aft Closure | G3 reinforced section | 0.184 | 425 - 453 Avg(3) 440 | 479 - 584 Avg(3) 523 |
| | | | | 189 - 324 Avg(3) 274 | |
| | Aft Skirt | 3-in. aft of G3 weld | 0.118 | 479 - 481 Avg(2) 480 | |
| | | | | 543 - 545 Avg(2) 544 | |
| | | | | 0.112 | |

TABLE XXVII

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER R490 (52 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|-----------------------|
| Forward Skirt | M1 - 3 |
| Forward Closure | M4 - 17 |
| Forward Cylinder | |
| At G1 Weld | M18 - 23 |
| At G2 Weld | M24 - 41 M54 - 65* |
| Aft Cylinder | |
| At G2 Weld | M42 - 53 M66 - 71 |
| At G3 Weld | M72 - 77 |
| Aft Closure | M78 - 92 |
| Aft Skirt | M93 - 95 |

TABLE XXVII (cont.)

| SPECIMEN NO | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft - lb | DEGREES | C D | Test Temp. |
|----------------|-------|----------|--------|-------|----------|---------|---------|-------|---------------|
| M-7 | 0.172 | 0.249 | 0.0428 | 270 | 11.54 | 0.962 | 154.7 | 0.069 | -40°F |
| M-10 | 0.176 | 0.224 | 0.0394 | 285 | 11.23 | 0.936 | 155.0 | 0.095 | -40°F |
| M-14 | 0.179 | 0.265 | 0.0474 | 296 | 14.04 | 1.170 | 152.5 | 0.054 | -40°F |
| M-30 | 0.163 | 0.235 | 0.0430 | 237 | 10.19 | 0.849 | 156.0 | 0.080 | -40°F |
| M-34 | 0.180 | 0.275 | 0.0495 | 267 | 13.21 | 1.101 | 153.2 | 0.043 | -40°F |
| M-38 | 0.177 | 0.284 | 0.0503 | 265 | 13.33 | 1.111 | 153.1 | 0.036 | -40°F |
| M-42 | 0.184 | 0.054 | 0.0099 | 192.7 | 1.908 | 0.159 | 166.2 | 0.263 | -40°F |
| M-46 | 0.184 | 0.096 | 0.0177 | 170.8 | 3.024 | 0.252 | 164.5 | 0.219 | -40°F |
| M-50 | 0.182 | 0.250 | 0.0455 | 261 | 11.83 | 0.990 | 154.4 | 0.068 | -40°F |
| M-54 | 0.197 | 0.282 | 0.0556 | 1310 | 73.08 | 6.09 | 119.1 | 0.040 | -40°F |
| M-58 | 0.197 | 0.227 | 0.0447 | 1250 | 56.04 | 4.67 | 126.3 | 0.093 | -40°F |
| M-62 | 0.195 | 0.266 | 0.0519 | 1536 | 79.32 | 6.61 | 116.2 | 0.054 | -40°F |
| M-78 | 0.186 | 0.287 | 0.0534 | 189 | 10.09 | 0.841 | 156.1 | 0.032 | -40°F |
| M-82 | 0.186 | 0.255 | 0.0474 | 308 | 14.62 | 1.218 | 152.0 | 0.064 | -40°F |
| M-86 | 0.186 | 0.241 | 0.0448 | 324 | 14.50 | 1.208 | 152.1 | 0.077 | -40°F |
| | | | | | | | | | |
| M-1 | 0.107 | 0.281 | 0.0301 | 570 | 17.16 | 1.43 | 149.9 | 0.049 | RT |
| M-2 | 0.108 | 0.271 | 0.0291 | 507 | 14.75 | 1.229 | 151.9 | 0.048 | RT |
| M-3 | 0.108 | 0.267 | 0.0288 | 471 | 13.57 | 1.131 | 152.9 | 0.052 | RT |
| M-4 | 0.113 | 0.278 | 0.0314 | 367 | 11.54 | 0.962 | 154.7 | 0.042 | RT |
| M-5 | 0.114 | 0.287 | 0.0327 | 374 | 12.23 | 1.019 | 154.1 | 0.033 | RT |

TABLE XXVII (cont.)

| SPECIMEN NO | WIDTH | DBN - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|-------------|-------|----------|--------|-------|--------|--------|---------|-------|------------|
| M-6 | 0.115 | 0.272 | 0.0313 | 386.9 | 12.11 | 1.009 | 154.2 | 0.049 | RT |
| M | 0.175 | 0.280 | 0.0490 | 377 | 18.48 | 1.54 | 148.8 | 0.039 | RT |
| M-11 | 0.178 | 0.273 | 0.0495 | 436 | 21.60 | 1.80 | 146.4 | 0.046 | RT |
| M-15 | 0.179 | 0.256 | 0.0458 | 330 | 16.05 | 1.338 | 150.8 | 0.064 | RT |
| M-18 | 0.179 | 0.263 | 0.0471 | 346 | 16.30 | 1.358 | 150.6 | 0.055 | RT |
| M-19 | 0.182 | 0.274 | 0.0499 | 420.8 | 21.00 | 1.75 | 146.8 | 0.044 | RT |
| M-20 | 0.182 | 0.256 | 0.0466 | 368 | 17.16 | 1.43 | 149.9 | 0.063 | RT |
| M-21 | 0.105 | 0.277 | 0.0291 | 343 | 10.00 | 0.833 | 156.2 | 0.042 | RT |
| M-22 | 0.107 | 0.274 | 0.0293 | 401 | 11.77 | 0.981 | 154.5 | 0.046 | RT |
| M-23 | 0.107 | 0.272 | 0.0291 | 435 | 12.66 | 1.055 | 153.7 | 0.048 | RT |
| M-24 | 0.108 | 0.270 | 0.0292 | 682 * | 19.92 | 1.66 | 147.6 | 0.046 | RT |
| M-25 | 0.109 | 0.282 | 0.0307 | 703 * | 21.60 | 1.80 | 146.4 | 0.039 | RT |
| M-26 | 0.109 | 0.295 | 0.0311 | 654 * | 20.34 | 1.695 | 147.3 | 0.034 | RT |
| M-27 | 0.109 | 0.179 | 0.0195 | 321 | 6.27 | 0.523 | 160.3 | 0.140 | RT |
| M-28 | 0.109 | 0.258 | 0.0281 | 466 | 13.10 | 1.092 | 153.3 | 0.062 | RT |
| M-29 | 0.109 | 0.271 | 0.0295 | 444 | 13.10 | 1.092 | 153.3 | 0.046 | RT |
| M-31 | 0.181 | 0.252 | 0.0456 | 352 | 16.06 | 1.338 | 150.8 | 0.067 | RT |
| M-39 | 0.182 | 0.259 | 0.0471 | 323 | 15.22 | 1.268 | 151.5 | 0.059 | RT |
| M-35 | 0.182 | 0.246 | 0.0448 | 366 | 16.42 | 1.368 | 150.5 | 0.073 | RT |
| M-43 | 0.184 | 0.256 | 0.0471 | 315 | 14.86 | 1.238 | 151.8 | 0.064 | RT |
| M-47 | 0.186 | 0.246 | 0.0458 | 333.9 | 15.34 | 1.278 | 151.4 | 0.072 | RT |

*Crack propagating in the chamber-hoop direction.

TABLE XXVII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|-------|--------|--------|-------|--------|--------|---------|-------|------------|
| M-51 | 0.185 | 0.261 | 0.0483 | 380 | 18.36 | 1.53 | 148.9 | 0.058 | RT |
| M-53 | 0.195 | 0.287 | 0.0560 | 1656 | 92.76 | 7.73 | 111.4 | 0.035 | RT |
| M-59 | 0.195 | 0.282 | 0.0552 | 1672 | 92.28 | 7.69 | 111.6 | 0.037 | RT |
| M-63 | 0.194 | 0.296 | 0.0574 | 1836 | 105.4 | 8.78 | 105.2 | 0.024 | RT |
| M-66 | 0.109 | 0.274 | 0.0299 | 379 | 11.34 | 0.945 | 154.9 | 0.046 | RT |
| M-67 | 0.109 | 0.275 | 0.0300 | 388 | 11.65 | 0.971 | 154.6 | 0.045 | RT |
| M-68 | 0.109 | 0.267 | 0.0291 | 379 | 11.03 | 0.919 | 155.2 | 0.053 | RT |
| M-69 | 0.109 | 0.272 | 0.0296 | 439 * | 13.00 | 1.083 | 153.4 | 0.047 | RT |
| M-70 | 0.110 | 0.260 | 0.0286 | 403 * | 11.54 | 0.962 | 154.7 | 0.060 | RT |
| M-71 | 0.110 | 0.252 | 0.0277 | 437 * | 12.11 | 1.009 | 154.2 | 0.064 | RT |
| M-72 | 0.106 | 0.243 | 0.0258 | 256 | 6.61 | 0.551 | 159.9 | 0.075 | RT |
| M-73 | 0.107 | 0.185 | 0.0198 | 284 | 5.63 | 0.469 | 161.1 | 0.114 | RT |
| M-74 | 0.107 | 0.254 | 0.0272 | 311 | 8.45 | 0.704 | 157.8 | 0.065 | RT |
| M-75 | 0.180 | 0.273 | 0.0491 | 260 | 12.77 | 1.064 | 153.6 | 0.045 | RT |
| M-76 | 0.185 | 0.275 | 0.0509 | 303 | 15.46 | 1.288 | 151.3 | 0.045 | RT |
| M-77 | 0.180 | 0.276 | 0.0497 | 303 | 15.10 | 1.258 | 151.6 | 0.051 | RT |
| M-78 | 0.184 | 0.192 | 0.0353 | 1091 | 27.60 | 2.30 | 142.4 | 0.127 | RT |
| M-79 | 0.185 | 0.287 | 0.0531 | 453 | 24.06 | 2.005 | 144.7 | 0.032 | RT |
| M-83 | 0.185 | 0.275 | 0.0509 | 441 | 22.44 | 1.87 | 145.8 | 0.047 | RT |
| M-87 | 0.184 | 0.274 | 0.0504 | 425 | 21.42 | 1.785 | 146.5 | 0.047 | RT |
| M-90 | 0.117 | 0.275 | 0.0322 | 123 | 3.98 | 0.332 | 163.2 | 0.043 | RT |

*Crack propagating in the chamber-hoop direction.

TABLE XXVII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|-------|--------|--------|------|--------|--------|---------|--------|------------|
| M-91 | 0.119 | 0.268 | 0.0319 | 481 | 15.34 | 1.278 | 151.4 | 0.063 | RT |
| M-92 | 0.119 | 0.238 | 0.0283 | 479 | 13.57 | 1.131 | 152.9 | 0.081 | RT |
| M-93 | 0.112 | 0.198 | 0.0221 | 543 | 12.00 | 1.000 | 154.3 | 0.120 | RT |
| M-94 | 0.112 | 0.273 | 0.0305 | 545 | 16.64 | 1.387 | 150.3 | 0.046 | RT |
| M-95 | 0.112 | 0.272 | 0.0304 | 141 | 4.30 | 0.358 | 162.8 | 0.048 | RT |
| | | | | | | | | | |
| M-8 | 0.175 | 0.256 | 0.0448 | 474 | 21.24 | 1.77 | 146.6 | 0.0634 | 200°F |
| M-12 | 0.178 | 0.271 | 0.0482 | 612 | 29.52 | 2.46 | 141.2 | 0.0465 | 200°F |
| M-16 | 0.179 | 0.260 | 0.0465 | 475 | 22.08 | 1.84 | 146.0 | 0.0583 | 200°F |
| M-32 | 0.180 | 0.264 | 0.0475 | 599 | 28.44 | 2.37 | 141.8 | 0.0499 | 200°F |
| M-36 | 0.176 | 0.252 | 0.0444 | 501 | 22.26 | 1.855 | 145.9 | 0.0586 | 200°F |
| M-40 | 0.179 | 0.230 | 0.0412 | 428 | 17.64 | 1.47 | 149.5 | 0.0866 | 200°F |
| M-44 | 0.183 | 0.243 | 0.0445 | 377 | 16.78 | 1.398 | 150.2 | 0.0765 | 200°F |
| M-48 | 0.184 | 0.255 | 0.0469 | 427 | 20.04 | 1.67 | 147.5 | 0.0658 | 200°F |
| M-52 | 0.185 | 0.247 | 0.0457 | 478 | 21.84 | 1.82 | 146.2 | 0.0673 | 200°F |
| M-56 | 0.195 | 0.276 | 0.0538 | 1840 | 99.24 | 8.27 | 107.7 | 0.0423 | 200°F |
| M-60 | 0.198 | 0.285 | 0.0564 | 2040 | 115.3 | 9.61 | 101.0 | 0.0335 | 200°F |
| M-64 | 0.196 | 0.252 | 0.0494 | 2000 | 99.00 | 8.25 | 107.8 | 0.0656 | 200°F |
| M-80 | 0.188 | 0.233 | 0.0438 | 584 | 25.56 | 2.13 | 143.1 | 0.0797 | 200°F |
| M-84 | 0.188 | 0.229 | 0.0430 | 505 | 21.72 | 1.81 | 146.3 | 0.0902 | 200°F |
| M-88 | 0.188 | 0.208 | 0.0391 | 479 | 18.72 | 1.56 | 148.6 | 0.1107 | 200°F |

TABLE XXVII (cont.)

[illegible]

TABLE XXVIII

PRECRACK CHARPY IMPACT DATA - 6Al-4V TITANIUM

| Minuteman Chamber S/N | Component | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|-----------|--------------------------|-------------------|-------------------------|-------------------------|-------------------------|
| | | | | -40 | RT | 200 |
| R312 | Fwd Skirt | | 0.109 | | 693 - 776 Avg(3) 737 | 320 |
| | | 3-in. fwd of G1 weld | 0.121 | | 535 - 554 Avg(3) 542 | |
| | | G1 reinforced section | 0.189 | 364 - 411 Avg(3) 390 | 433 - 493 Avg(3) 467 | 528 - 760 Avg(3) 623 |
| | Fwd Cyl | | 0.186 | | 362 - 456 Avg(3) 420 | 827 - 972 Avg(3) 908 |
| | | 3-in. aft of G1 weld | 0.107 | | 468 - 540 Avg(3) 509 | |
| | | 3-in. fwd of G2 weld | 0.108 | | 526 - 532 Avg(3) 529 | |
| | Aft Cyl | Ditto hoop | | | 388 - 468 Avg(3) 436 | |
| | | G2 reinforced section | 0.186 | 265 - 309 Avg(3) 292 | 340 - 409 Avg(3) 368 | 468 - 538 Avg(3) 508 |
| | | G2 reinforced section | 0.185 | 248 - 257 Avg(3) 254 | 316 - 341 Avg(3) 326 | 708 - 733 Avg(2) 720 |
| | | 3-in. aft of G2 weld | 0.109 | | 429 - 487 Avg(3) 463 | 626 - 662 Avg(2) 644 |
| | | Ditto hoop | 0.107 | | 386 - 443 Avg(3) 414 | |
| | | | | | 414 - 539 Avg(3) 467 | |

TABLE XXVIII (cont.)

| <u>Minuteman Chamber</u> <u>S/N</u> | <u>Component</u> | <u>Specimen</u> <u>Location</u> | <u>Wall</u> <u>Thickness</u> | <u>Test Temperature, °F</u> | | |
|--|------------------------|------------------------------------|---------------------------------|-----------------------------|-------------------------|---|
| | | | | <u>-40</u> | <u>RT</u> | <u>200</u> <u>320</u> |
| R512 | Aft Cyl (continued) | 3-in. fwd of G3 weld | 0.110 | | 405 - 436 Avg(3) 424 | |
| | | G3 reinforced section | 0.187 | | 368 - 372 Avg(3) 370 | |
| | Aft Closure | G3 reinforced section | 0.180 | 430 - 496 Avg(3) 468 | 577 - 661 Avg(3) 607 | 670 - 722 Avg(3) 689 895 - 1075 Avg(3) 978 |
| | | 3-in. aft of G3 weld | 0.111 | | 670 - 701 Avg(3) 683 | |
| | Aft Skirt | - | 0.118 | | 558 - 778 Avg(3) 668 | |

TABLE XXIX

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER R512 (52-IN.-DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Skirt | P1 - 3 |
| Forward Closure | P4 - 18 |
| Forward Cylinder | |
| At G1 Weld | P19 - 24 |
| At G2 Weld | P25 - 38 |
| Aft Cylinder | |
| At G2 Weld | P40 - 54 |
| At G3 Weld | P55 - 60 |
| Aft Closure | P61 - 75 |
| Aft Skirt | P76 - 78 |

TABLE XXIX (cont.)

| SPECIMEN NO. | WIDTH: | DBN - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|----------------|----------|--------|-----|--------|--------|---------|-------|------------|
| P-28 | 0.190 0.172 | 0.255 | 0.0462 | 265 | 12.23 | 1.019 | 154.1 | 0.060 | -40°F |
| P-32 | 0.192 0.175 | 0.274 | 0.0503 | 303 | 15.22 | 1.268 | 151.5 | 0.043 | -40°F |
| P-36 | 0.192 0.180 | 0.266 | 0.0497 | 309 | 15.34 | 1.278 | 151.4 | 0.051 | -40°F |
| P-40 | 0.194 0.180 | 0.271 | 0.0507 | 256 | 13.00 | 1.083 | 153.4 | 0.045 | -40°F |
| P-44 | 0.195 0.181 | 0.239 | 0.0449 | 248 | 11.12 | 0.927 | 155.1 | 0.077 | -40°F |
| P-48 | 0.195 0.182 | 0.255 | 0.0481 | 257 | 12.34 | 1.028 | 154.0 | 0.060 | -40°F |
| P-7 | 0.184 | 0.2560 | 0.0471 | 395 | 18.60 | 1.55 | 148.7 | | -40°F |
| P-11 | 0.190 | 0.2268 | 0.0431 | 364 | 15.696 | 1.308 | 151.1 | | -40°F |
| P-15 | 0.190 | 0.2397 | 0.0455 | 411 | 18.72 | 1.56 | 148.6 | | -40°F |
| P-61 | 0.177 | 0.2370 | 0.0419 | 430 | 18.00 | 1.50 | 149.2 | | -40°F |
| P-65 | 0.181 | 0.2330 | 0.0422 | 478 | 20.16 | 1.68 | 147.4 | | -40°F |
| P-69 | 0.181 | 0.2460 | 0.0445 | 496 | 22.08 | 1.84 | 146.0 | | -40°F |
| | | | | | | | | | |
| P-1 | 0.109 | 0.2604 | 0.0284 | 693 | 19.68 | 1.64 | 147.8 | | RT |
| P-2 | 0.109 | 0.2539 | 0.0277 | 741 | 20.52 | 1.71 | 147.2 | | RT |
| P-3 | 0.109 | 0.2592 | 0.0283 | 776 | 21.96 | 1.83 | 146.1 | | RT |
| P-4 | 0.121 | 0.2537 | 0.0307 | 535 | 16.416 | 1.368 | 150.5 | | RT |
| P-5 | 0.120 | 0.2528 | 0.0303 | 554 | 16.776 | 1.398 | 150.2 | | RT |
| P-6 | 0.121 | 0.2623 | 0.0317 | 537 | 17.016 | 1.418 | 150.0 | | RT |
| P-8 | 0.185 | 0.2392 | 0.0443 | 474 | 21.00 | 1.75 | 146.8 | | RT |
| P-12 | 0.190 | 0.2263 | 0.0430 | 433 | 18.60 | 1.55 | 148.7 | | RT |

TABLE XXIX (cont.)

| SPECIMEN NO | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|----------------|----------------|--------|--------|-------|--------|--------|---------|-------|---------------|
| P-16 | 0.189 | 0.2513 | 0.0475 | 493 | 23.40 | 1.95 | 145.1 | | RT |
| P-19 | 0.186 | 0.2435 | 0.0453 | 362 | 16.416 | 1.368 | 150.5 | | RT |
| P-20 | 0.187 | 0.2492 | 0.0466 | 443 | 20.64 | 1.72 | 147.1 | | RT |
| P-21 | 0.185 | 0.2473 | 0.0458 | 456 | 20.88 | 1.74 | 146.9 | | RT |
| P-22 | 0.106 | 0.2643 | 0.0280 | 468 | 13.104 | 1.092 | 153.3 | | RT |
| P-23 | 0.107 | 0.2572 | 0.0275 | 519 | 14.268 | 1.189 | 152.3 | | RT |
| P-25 | 0.108 | 0.274 | 0.0296 | 526 | 15.58 | 1.298 | 151.2 | 0.046 | RT |
| P-26 | 0.108 | 0.271 | 0.0293 | 532 | 15.58 | 1.298 | 151.2 | 0.049 | RT |
| P-27 | 0.108 | 0.273 | 0.0295 | 528 | 15.58 | 1.298 | 151.2 | 0.046 | RT |
| P-29 | 0.190 0.180 | 0.255 | 0.0472 | 356 | 16.78 | 1.398 | 150.2 | 0.060 | RT |
| P-33 | 0.191 0.179 | 0.255 | 0.0472 | 340 | 16.06 | 1.338 | 150.8 | 0.060 | RT |
| P-37 | 0.192 0.184 | 0.270 | 0.0508 | 409 | 20.76 | 1.73 | 147.0 | 0.047 | RT |
| P-41 | 0.194 0.187 | 0.218 | 0.0415 | 316 | 13.10 | 1.092 | 153.3 | 0.098 | RT |
| P-45 | 0.195 0.186 | 0.232 | 0.0442 | 320 | 14.15 | 1.179 | 152.4 | 0.085 | RT |
| P-49 | 0.194 0.186 | 0.250 | 0.0475 | 341 | 16.18 | 1.348 | 150.7 | 0.068 | RT |
| P-52 | 0.108 | 0.272 | 0.0294 | 412 | 12.11 | 1.009 | 154.2 | 0.048 | RT |
| P-53 | 0.109 | 0.262 | 0.0286 | 386 | 11.03 | 0.919 | 155.2 | 0.056 | RT |
| P-54 | 0.109 | 0.267 | 0.0291 | 443 | 12.88 | 1.073 | 153.5 | 0.050 | RT |
| P-79 | 0.107 | 0.273 | 0.0292 | 452 * | 13.21 | 1.101 | 153.2 | 0.045 | RT |
| P-80 | 0.106 | 0.283 | 0.0300 | 468 * | 14.04 | 1.170 | 152.5 | 0.034 | RT |
| P-81 | 0.106 | 0.260 | 0.276 | 388 * | 10.70 | 0.892 | 155.5 | 0.057 | RT |

*Crack propagating in the chamber hoop-direction

TABLE XXIX (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|-------|--------|--------|-------|--------|--------|---------|-------|------------|
| P-82 | 0.108 | 0.268 | 0.0289 | 539 * | 15.58 | 1.298 | 151.2 | 0.049 | RT |
| P-83 | 0.107 | 0.268 | 0.0287 | 449 * | 12.88 | 1.073 | 153.5 | 0.053 | RT |
| P-84 | 0.107 | 0.261 | 0.279 | 414 * | 11.54 | 0.962 | 154.7 | 0.059 | RT |
| P-24 | 0.107 | 0.2653 | 0.0284 | 540 | 15.336 | 1.278 | 151.4 | | RT |
| P-55 | 0.110 | 0.2471 | 0.0272 | 405 | 11.028 | 0.919 | 155.2 | | RT |
| P-56 | 0.110 | 0.2648 | 0.0291 | 431 | 12.552 | 1.046 | 153.8 | | RT |
| P-57 | 0.110 | 0.2524 | 0.0278 | 436 | 12.108 | 1.009 | 154.2 | | RT |
| P-58 | 0.187 | 0.2190 | 0.0410 | 368 | 15.096 | 1.258 | 151.6 | | RT |
| P-59 | 0.189 | 0.2451 | 0.0463 | 370 | 17.148 | 1.429 | 149.9 | | RT |
| P-60 | 0.187 | 0.2398 | 0.0448 | 372 | 16.664 | 1.387 | 150.3 | | RT |
| P-62 | 0.173 | 0.2429 | 0.0420 | 583 | 24.48 | 2.04 | 144.4 | | RT |
| P-66 | 0.180 | 0.2531 | 0.0456 | 661 | 30.12 | 2.51 | 140.8 | | RT |
| P-70 | 0.181 | 0.2341 | 0.0424 | 577 | 24.48 | 2.04 | 144.4 | | RT |
| P-73 | 0.111 | 0.2512 | 0.0279 | 701 | 19.56 | 1.63 | 148.0 | | RT |
| P-74 | 0.111 | 0.2529 | 0.0292 | 670 | 19.56 | 1.63 | 148.0 | | RT |
| P-75 | 0.111 | 0.2611 | 0.0290 | 677 | 19.62 | 1.635 | 147.9 | | RT |
| P-76 | 0.118 | 0.2658 | 0.0314 | 558 | 17.52 | 1.46 | 149.6 | | RT |
| P-77 | 0.118 | 0.2649 | 0.0313 | 667 | 20.88 | 1.74 | 146.9 | | RT |
| P-78 | 0.118 | 0.2605 | 0.0307 | 778 | 23.88 | 1.99 | 144.8 | | RT |
| | | | | | | | | | |
| | | | | | | | | | |

*Crack propagating in the chamber hoop-direction

TABLE XXIX (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|-----------------|----------------|--------|--------|------|--------|--------|---------|-------|---------------|
| P-30 | 0.190 0.180 | 0.244 | 0.0451 | 468 | 21.12 | 1.76 | 146.7 | 0.073 | 200°F |
| P-34 | 0.191 0.180 | 0.249 | 0.0462 | 538 | 24.84 | 2.07 | 144.1 | 0.069 | 200°F |
| P-38 | 0.191 0.183 | 0.255 | 0.0477 | 518 | 24.72 | 2.06 | 144.2 | 0.062 | 200°F |
| P-42 | 0.194 0.187 | 0.242 | 0.0461 | 487 | 22.44 | 1.87 | 145.8 | 0.073 | 200°F |
| P-46 | 0.194 0.184 | 0.213 | 0.0403 | 429 | 17.28 | 1.44 | 149.8 | 0.104 | 200°F |
| P-50 | 0.194 0.184 | 0.259 | 0.0490 | 478 | 23.40 | 1.95 | 145.1 | 0.058 | 200°F |
| P-9 | 0.186 | 0.2379 | 0.0442 | 581 | 25.68 | 2.14 | 143.5 | | 200°F |
| P-13 | 0.188 | 0.2118 | 0.0398 | 528 | 21.00 | 1.75 | 146.8 | | 200°F |
| P-17 | 0.190 | 0.2638 | 0.0501 | 760 | 38.10 | 3.175 | 136.1 | | 200°F |
| P-63 | 0.174 | 0.2379 | 0.0414 | 675 | 27.96 | 2.33 | 142.2 | | 200°F |
| P-67 | 0.180 | 0.2273 | 0.0409 | 722 | 29.52 | 2.46 | 141.2 | | 200°F |
| P-71 | 0.181 | 0.2325 | 0.0421 | 670 | 28.20 | 2.35 | 142.0 | | 200°F |
| | | | | | | | | | |
| P-10 | 0.189 | 0.2453 | 0.0464 | 972 | 45.12 | 3.76 | 132.2 | | 320°F |
| P-14 | 0.189 | 0.2323 | 0.0439 | 827 | 36.30 | 3.025 | 137.1 | | 320°F |
| P-18 | 0.190 | 0.2573 | 0.0489 | 926 | 45.30 | 3.775 | 132.1 | | 320°F |
| P-64 | 0.182 | 0.2186 | 0.0398 | 1075 | 42.78 | 3.565 | 133.5 | | 320°F |
| P-68 | 0.181 | 0.2126 | 0.0385 | 895 | 34.44 | 2.87 | 138.2 | | 320°F |
| P-72 | 0.182 | 0.2319 | 0.0422 | 963 | 40.62 | 3.385 | 134.7 | | 320°F |
| P-31 | 0.192 0.176 | 0.255 | 0.0469 | 733 | 34.4 | 2.87 | 138.2 | | 320°F |
| | | | | | | | | | |

TABLE XXIX (cont.)

[illegible]

TABLE XXX

PRECRACK CHARPY IMPACT DATA - 6Al-4V TITANIUM

| <u>Minuteman Chamber S/N</u> | <u>Specimen Location</u> | <u>Wall Thickness</u> | <u>Test Temperature, °F</u> | | |
|----------------------------------|------------------------------|---------------------------|-----------------------------|-------------------------|-------------------------|
| | | | <u>-40</u> | <u>RT</u> | <u>200</u> |
| R516 | Fwd Skirt | 0.104 | | 643 - 663 Avg(3) 655 | 320 |
| | | | | | |
| | Fwd Closure | 2-in. fwd of G1 weld | | 371 - 473 Avg(3) 420 | |
| | | | | | |
| | G1 reinforced section | 0.185 | 287 - 355 Avg(3) 311 | 356 - 428 Avg(3) 394 | 489 - 573 Avg(3) 528 |
| | | | | | 670 - 975 Avg(3) 795 |
| | Fwd Cyl | G1 reinforced section | | 373 - 644 Avg(3) 465 | |
| | | | | | |
| | 2-in. aft of G1 weld | 0.107 | | 404 - 428 Avg(3) 415 | |
| | | | | | |
| | 3-in. fwd of G2 weld | 0.106 | | 315 - 375 Avg(3) 349 | |
| | | | | | |
| | Ditto hoop | 0.104 | | 393 - 501 Avg(3) 459 | |
| | | | | | |
| | G2 reinforced section | 0.182 | 214 - 272 Avg(3) 252 | 328 - 405 Avg(3) 358 | 390 - 458 Avg(3) 434 |
| | | | | | 647 - 709 Avg(3) 671 |
| | Aft Cyl | G2 reinforced section | 339 - 345 Avg(3) 341 | 389 - 457 Avg(3) 429 | 526 - 576 Avg(3) 553 |
| | | | | | 687 - 796 Avg(3) 746 |
| | 3-in. aft of G2 weld | 0.107 | | 384 - 482 Avg(3) 444 | |
| | | | | | |
| | Ditto hoop | 0.105 | | 345 - 400 Avg(3) 374 | |
| | | | | | |

TABLE XXX (cont.)

| Minuteman Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|------------------------|--------------------------|----------------------|-------------------------|-------------------------|
| | | | -40 | RT | 200 |
| R516 | Aft Cyl (continued) | 3-in. fwd of G3 weld | 0.109 | 426 - 493 Avg(3) 469 | 320 |
| | | | | 338 - 381 Avg(3) 362 | |
| | | | | 320 - 381 Avg(3) 355 | 774 - 826 Avg(3) 798 |
| | Aft Closure | G3 reinforced section | 0.190 | 384 - 392 Avg(3) 389 | 546 - 644 Avg(3) 591 |
| | | | | 500 - 526 Avg(3) 510 | |
| | | | | 530 - 555 Avg(3) 542 | |
| | Aft Skirt | 3-in. aft of G3 weld | 0.118 | | |
| | | | | | |
| | | | | | |
| | | - | 0.116 | | |
| | | | | | |
| | | | | | |

TABLE XXXI

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER R516 (52 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Skirt | R1 - 3 |
| Forward Closure | R4 - 18 |
| Forward Cylinder | |
| At G1 Weld | R19 - 24 |
| At G2 Weld | R25 - 42 |
| Aft Cylinder | |
| At G2 Weld | R43 - 60 |
| At G3 Weld | R61 - 66 |
| Aft Closure | R67 - 81 |
| Aft Skirt | R82 - 84 |

TABLE XXXI (cont.)

| SPECIMEN NO. | WIDTH | DBH - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C D | Test Temp. |
|--------------|----------------|----------|--------|-----|----------|----------|---------|-------|------------|
| R-7 | 0.191 0.172 | 0.274 | 0.0497 | 355 | 17.64 | 1.47 | 149.5 | 0.043 | -40°F |
| R-11 | 0.192 0.172 | 0.267 | 0.0481 | 287 | 13.80 | 1.150 | 152.7 | 0.046 | -40°F |
| R-15 | 0.193 0.173 | 0.275 | 0.0503 | 291 | 14.62 | 1.218 | 152.0 | 0.042 | -40°F |
| R-31 | 0.187 0.167 | 0.282 | 0.0499 | 214 | 10.70 | 0.892 | 155.5 | 0.037 | -40°F |
| R-35 | 0.190 0.168 | 0.276 | 0.0494 | 270 | 13.33 | 1.111 | 153.1 | 0.041 | -40°F |
| R-39 | 0.191 0.170 | 0.293 | 0.0529 | 272 | 14.39 | 1.199 | 152.2 | 0.024 | -40°F |
| R-43 | 0.189 0.178 | 0.285 | 0.0523 | 340 | 17.76 | 1.48 | 149.4 | 0.033 | -40°F |
| R-47 | 0.191 0.181 | 0.289 | 0.0538 | 339 | 18.24 | 1.52 | 149.0 | 0.029 | -40°F |
| R-51 | 0.190 0.179 | 0.260 | 0.0480 | 345 | 16.54 | 1.378 | 150.4 | 0.056 | -40°F |
| R-67 | 0.193 0.179 | 0.262 | 0.0487 | 320 | 15.58 | 1.298 | 151.2 | 0.057 | -40°F |
| R-71 | 0.194 0.182 | 0.269 | 0.0506 | 363 | 18.36 | 1.53 | 148.9 | 0.050 | -40°F |
| R-75 | 0.197 0.187 | 0.274 | 0.0526 | 381 | 20.04 | 1.67 | 147.5 | 0.045 | -40°F |
| | | | | | | | | | |
| R-1 | 0.104 | 0.264 | 0.0275 | 656 | 18.00 | 1.50 | 149.2 | 0.045 | RT |
| R-2 | 0.104 | 0.267 | 0.0277 | 645 | 17.88 | 1.49 | 149.3 | 0.053 | RT |
| R-3 | 0.105 | 0.270 | 0.0284 | 663 | 18.84 | 1.57 | 148.5 | 0.051 | RT |
| R-4 | 0.115 | 0.269 | 0.0309 | 473 | 14.62 | 1.218 | 152.0 | 0.050 | RT |
| R-5 | 0.115 | 0.276 | 0.0317 | 417 | 13.21 | 1.101 | 153.2 | 0.042 | RT |
| R-6 | 0.115 | 0.258 | 0.0297 | 371 | 11.03 | 0.919 | 155.2 | 0.060 | RT |
| R-8 | 0.191 0.176 | 0.199 | 0.0365 | 356 | 13.00 | 1.083 | 153.4 | 0.118 | RT |
| R-12 | 0.191 0.176 | 0.230 | 0.0422 | 398 | 16.78 | 1.398 | 150.2 | 0.088 | RT |

TABLE XXXI (cont.)

| SPECIMEN NO | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D | Test Temp. |
|-------------|----------------|--------|--------|-------|--------|--------|---------|-------|------------|
| R-16 | 0.192 0.181 | 0.265 | 0.0494 | 428 | 21.12 | 1.76 | 146.7 | 0.051 | RT |
| R-19 | 0.191 0.180 | 0.243 | 0.0451 | 644 | 29.04 | 2.42 | 141.5 | 0.075 | RT |
| R-20 | 0.190 0.182 | 0.262 | 0.0487 | 377 | 18.36 | 1.53 | 148.9 | 0.057 | RT |
| R-21 | 0.190 0.179 | 0.261 | 0.0482 | 373 | 18.00 | 1.50 | 149.2 | 0.058 | RT |
| R-22 | 0.108 | 0.262 | 0.0283 | 412 | 11.65 | 0.971 | 154.6 | 0.057 | RT |
| R-23 | 0.107 | 0.254 | 0.0272 | 428 | 11.65 | 0.971 | 154.6 | 0.066 | RT |
| R-24 | 0.107 | 0.260 | 0.0278 | 404 | 11.23 | 0.936 | 155.0 | 0.060 | RT |
| R-25 | 0.103 | 0.267 | 0.0275 | 393 * | 10.81 | 0.901 | 155.4 | 0.054 | RT |
| R-26 | 0.104 | 0.277 | 0.0288 | 483 * | 13.92 | 1.160 | 152.6 | 0.042 | RT |
| R-27 | 0.105 | 0.271 | 0.0285 | 501 * | 14.27 | 1.189 | 152.3 | 0.049 | RT |
| R-28 | 0.104 | 0.245 | 0.0255 | 315 | 8.02 | 0.668 | 158.3 | 0.072 | RT |
| R-29 | 0.106 | 0.265 | 0.0281 | 356 | 10.00 | 0.833 | 156.2 | 0.055 | RT |
| R-30 | 0.106 | 0.257 | 0.0272 | 375 | 10.19 | 0.849 | 156.0 | 0.062 | RT |
| R-32 | 0.190 0.173 | 0.243 | 0.0441 | 405 | 17.88 | 1.49 | 149.3 | 0.086 | RT |
| R-36 | 0.190 0.174 | 0.241 | 0.0439 | 328 | 14.39 | 1.199 | 152.2 | 0.077 | RT |
| R-40 | 0.190 0.176 | 0.239 | 0.0437 | 340 | 14.86 | 1.238 | 151.8 | 0.077 | RT |
| R-44 | 0.190 0.186 | 0.261 | 0.0491 | 457 | 22.44 | 1.87 | 145.8 | 0.057 | RT |
| R-48 | 0.190 0.184 | 0.254 | 0.0475 | 440 | 20.88 | 1.74 | 146.9 | 0.065 | RT |
| R-52 | 0.190 0.184 | 0.236 | 0.0441 | 389 | 17.16 | 1.43 | 149.9 | 0.082 | RT |
| R-55 | 0.106 | 0.260 | 0.0276 | 384 | 10.60 | 0.883 | 155.6 | 0.060 | RT |
| R-56 | 0.108 | 0.267 | 0.0288 | 467 | 13.45 | 1.121 | 153.0 | 0.050 | RT |

*Crack propagating in the chamber hoop-direction.

TABLE XXXI (cont.)

| SPECIMEN NO. | WIDTH | DBH - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|----------------|----------|--------|-------|--------|--------|---------|-------|------------|
| R-57 | 0.109 | 0.276 | 0.0301 | 482 | 14.50 | 1.208 | 152.1 | 0.045 | RT |
| R-58 | 0.104 | 0.264 | 0.0275 | 345 * | 9.50 | 0.792 | 156.7 | 0.055 | RT |
| R-59 | 0.105 | 0.279 | 0.0293 | 376 * | 11.03 | 0.919 | 155.2 | 0.041 | RT |
| R-60 | 0.105 | 0.263 | 0.0276 | 400 * | 11.03 | 0.919 | 155.2 | 0.056 | RT |
| R-61 | 0.109 | 0.266 | 0.0290 | 426 | 12.34 | 1.028 | 154.0 | 0.052 | RT |
| R-62 | 0.109 | 0.260 | 0.0283 | 488 | 13.80 | 1.150 | 152.7 | 0.060 | RT |
| R-63 | 0.110 | 0.267 | 0.0294 | 493 | 14.50 | 1.208 | 152.1 | 0.053 | RT |
| R-64 | 0.193 0.177 | 0.238 | 0.0440 | 338 | 14.88 | 1.248 | 151.7 | 0.080 | RT |
| R-65 | 0.195 0.185 | 0.249 | 0.0473 | 381 | 18.00 | 1.50 | 149.2 | 0.069 | RT |
| R-66 | 0.195 0.185 | 0.252 | 0.0479 | 368 | 17.64 | 1.47 | 149.5 | 0.067 | RT |
| R-68 | 0.193 0.186 | 0.235 | 0.0447 | 384 | 17.16 | 1.43 | 149.9 | 0.083 | RT |
| R-72 | 0.194 0.185 | 0.233 | 0.0442 | 391 | 17.28 | 1.44 | 149.8 | 0.085 | RT |
| R-76 | 0.195 0.187 | 0.261 | 0.0499 | 392 | 19.56 | 1.63 | 148.0 | 0.058 | RT |
| R-79 | 0.119 | 0.270 | 0.0321 | 526 | 16.90 | 1.408 | 150.1 | 0.049 | RT |
| R-80 | 0.118 | 0.272 | 0.0321 | 504 | 16.18 | 1.348 | 150.7 | 0.047 | RT |
| R-81 | 0.118 | 0.262 | 0.0309 | 500 | 15.46 | 1.288 | 151.3 | 0.058 | RT |
| R-82 | 0.116 | 0.279 | 0.0324 | 530 | 17.16 | 1.43 | 149.9 | 0.042 | RT |
| R-83 | 0.116 | 0.277 | 0.0321 | 542 | 17.40 | 1.45 | 149.7 | 0.044 | RT |
| R-84 | 0.116 | 0.255 | 0.0296 | 555 | 16.42 | 1.368 | 150.5 | 0.064 | RT |
| | | | | | | | | | |
| | | | | | | | | | |

*Cracking propagating in the chamber hoop-direction.

TABLE XXXI (cont.)

| SPECIMEN NO | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|----------------|----------------|--------|--------|-----|--------|--------|---------|-------|---------------|
| R-9 | 0.192 0.177 | 0.252 | 0.0465 | 573 | 26.64 | 2.42 | 141.5 | 0.066 | 200°F |
| R-13 | 0.193 0.180 | 0.217 | 0.0405 | 489 | 19.80 | 1.65 | 147.7 | 0.102 | 200°F |
| R-17 | 0.193 0.177 | 0.237 | 0.0438 | 523 | 22.92 | 1.91 | 145.5 | 0.077 | 200°F |
| R-33 | 0.191 0.174 | 0.231 | 0.0422 | 458 | 19.32 | 1.61 | 148.2 | 0.086 | 200°F |
| R-37 | 0.190 0.174 | 0.233 | 0.0424 | 453 | 19.20 | 1.60 | 148.3 | 0.086 | 200°F |
| R-41 | 0.191 0.176 | 0.188 | 0.0345 | 390 | 13.45 | 1.121 | 153.0 | 0.030 | 200°F |
| R-45 | 0.191 0.184 | 0.253 | 0.0474 | 562 | 26.64 | 2.22 | 143.0 | 0.066 | 200°F |
| R-49 | 0.190 0.184 | 0.244 | 0.0456 | 576 | 26.28 | 2.19 | 143.2 | 0.077 | 200°F |
| R-53 | 0.190 0.184 | 0.243 | 0.0454 | 526 | 23.88 | 1.99 | 144.8 | 0.076 | 200°F |
| R-69 | 0.194 0.184 | 0.241 | 0.0455 | 546 | 24.84 | 2.07 | 144.1 | 0.078 | 200°F |
| R-73 | 0.196 0.187 | 0.249 | 0.0477 | 584 | 27.84 | 2.32 | 142.3 | 0.071 | 200°F |
| R-77 | 0.195 0.186 | 0.264 | 0.0503 | 644 | 32.40 | 2.70 | 139.4 | 0.057 | 200°F |
| | | | | | | | | | |
| R-10 | 0.192 0.174 | 0.253 | 0.0463 | 975 | 45.12 | 3.76 | 132.2 | 0.065 | 320°F |
| R-14 | 0.194 0.177 | 0.217 | 0.0403 | 670 | 27.0 | 2.25 | 142.8 | 0.103 | 320°F |
| R-18 | 0.193 0.173 | 0.212 | 0.0388 | 739 | 28.68 | 2.39 | 141.7 | 0.107 | 320°F |
| R-34 | 0.191 0.169 | 0.240 | 0.0432 | 647 | 27.96 | 2.33 | 142.2 | 0.081 | 320°F |
| R-38 | 0.192 0.172 | 0.250 | 0.0455 | 709 | 32.28 | 2.69 | 139.5 | 0.068 | 320°F |
| R-42 | 0.192 0.172 | 0.252 | 0.0459 | 656 | 30.82 | 2.51 | 140.6 | 0.068 | 320°F |
| R-46 | 0.191 0.181 | 0.262 | 0.0487 | 754 | 36.72 | 3.06 | 136.9 | 0.058 | 320°F |
| R-50 | 0.190 0.180 | 0.265 | 0.0490 | 796 | 39.00 | 3.25 | 135.6 | 0.053 | 320°F |

TABLE XXXI (cont.)

[illegible]

TABLE XXII

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| Minuteman Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|--------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| | | | -40 | RT | 200 |
| R543 | Fwd Skirt | - | | 700 - 732 Avg(3) 714 | 320 |
| | | | | | |
| | Fwd Closure | 3-in. fwd of G1 weld | | 448 - 504 Avg(3) 484 | |
| | | | | | |
| | G1 reinforced section | 0.185 | 286 - 424 Avg(3) 346 | 427 - 480 Avg(3) 447 | 528 - 683 Avg(3) 619 |
| | | | | | 839 - 928 Avg(3) 872 |
| | G1 reinforced section | 0.185 | 262 - 353 Avg(3) 307 | 394 - 436 Avg(3) 419 | 522 - 592 Avg(3) 554 |
| | | | | | 820 - 917 Avg(3) 861 |
| | 3-in. aft of G1 weld | 0.106 | | 401 - 500 Avg(3) 447 | |
| | | | | | |
| | Ditto hoop | | | 361 - 507 Avg(3) 450 | |
| | | | | | |
| | 3-in. fwd of G2 weld | 0.105 | | 351 - 496 Avg(3) 445 | |
| | | | | | |
| | G2 reinforced section | 0.182 | | 289 - 393 Avg(3) 352 | |
| | | | | | |
| | G2 reinforced section | 0.185 | | 247 - 302 Avg(3) 280 | |
| | | | | | |
| | 3-in. aft of G2 weld | 0.107 | | 360 - 371 Avg(2) 366 | |
| | | | | | |
| | 3-in. fwd of G3 weld | 0.104 | | 336 - 351 Avg(3) 343 | |
| | | | | | |
| | Ditto Hoop | 0.105 | | 546 - 646 Avg(3) 602 | |
| | | | | | |

TABLE XXII (cont.)

| Minuteman Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|-------------------------|-------------------|-------------------------|-------------------------|--------------------------|
| | | | -40 | RT | 200 |
| R543 | Aft Cyl (continued) | 0.185 | 226 - 252 Avg(3) 236 | 269 - 361 Avg(3) 303 | 331 - 473 Avg(2) 402 |
| | | | | | 516 - 599 Avg(3) 565 |
| | Aft Closure | 0.190 | 333 - 352 Avg(3) 341 | 435 - 475 Avg(3) 458 | 625 - 677 Avg(3) 648 |
| | | | | | 798 - 1052 Avg(3) 930 |
| | 3-in. aft of G3 weld | 0.118 | | 491 - 583 Avg(3) 554 | |
| | | | | | |
| Aft Skirt | - | 0.113 | | 722 - 770 Avg(3) 753 | |

TABLE XXXIII

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER R543 (52-IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|----------------------|
| Forward Skirt | S1 - 3 |
| Forward Closure | S4 - 18 |
| Forward Cylinder | |
| At G1 Weld | S19 - 33 S82 - 84 |
| At G2 Weld | S34 - 39 |
| Aft Cylinder | |
| At G2 Weld | S40 - 45 |
| At G3 Weld | S46 - 60 S79 - 81 |
| Aft Closure | S61 - 75 |
| Aft Skirt | S76 - 78 |

TABLE XXXIII (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|-----------------|----------------|----------|--------|-----|--------|--------|---------|-------|---------------|
| S-7 | 0.187 0.174 | 0.254 | 0.0458 | 286 | 13.10 | 1,092 | 153.3 | 0.065 | -40°F |
| S-11 | 0.188 0.179 | 0.268 | 0.0492 | 424 | 20.88 | 1.74 | 146.9 | 0.049 | -40°F |
| S-15 | 0.189 0.177 | 0.256 | 0.0468 | 328 | 15.34 | 1.278 | 151.4 | 0.062 | -40°F |
| S-19 | 0.186 0.177 | 0.225 | 0.0408 | 262 | 10.70 | 0.892 | 155.5 | 0.090 | -40°F |
| S-23 | 0.189 0.185 | 0.242 | 0.0457 | 307 | 14.04 | 1.170 | 152.5 | 0.073 | -40°F |
| S-27 | 0.189 0.184 | 0.251 | 0.0468 | 353 | 16.54 | 1.378 | 150.4 | 0.075 | -40°F |
| S-49 | 0.190 0.186 | 0.246 | 0.0462 | 252 | 11.65 | 0.971 | 154.6 | 0.070 | -40°F |
| S-53 | 0.190 0.180 | 0.188 | 0.0348 | 230 | 8.02 | 0.668 | 158.3 | 0.129 | -40°F |
| S-57 | 0.193 0.183 | 0.245 | 0.0461 | 226 | 10.40 | 0.867 | 155.8 | 0.071 | -40°F |
| S-61 | 0.193 0.184 | 0.260 | 0.0516 | 333 | 17.16 | 1.43 | 149.9 | 0.055 | -40°F |
| S-65 | 0.195 0.187 | 0.268 | 0.0512 | 352 | 18.00 | 1.50 | 149.2 | 0.050 | -40°F |
| S-69 | 0.193 0.183 | 0.259 | 0.0487 | 337 | 16.42 | 1.368 | 150.5 | 0.059 | -40°F |
| | | | | | | | | | |
| S-1 | 0.113 | 0.259 | 0.0293 | 700 | 20.52 | 1.71 | 147.2 | 0.058 | RT |
| S-2 | 0.114 | 0.262 | 0.0299 | 710 | 21.24 | 1.79 | 146.5 | 0.054 | RT |
| S-3 | 0.114 | 0.259 | 0.0295 | 732 | 21.60 | 1.80 | 146.4 | 0.060 | RT |
| S-4 | 0.115 | 0.272 | 0.0314 | 504 | 15.82 | 1.318 | 151.0 | 0.046 | RT |
| S-5 | 0.114 | 0.261 | 0.0298 | 499 | 14.86 | 1.238 | 151.8 | 0.058 | RT |
| S-6 | 0.113 0.113 | 0.268 | 0.0303 | 448 | 13.58 | 1.131 | 152.9 | 0.049 | RT |
| S-8 | 0.189 0.177 | 0.259 | 0.0474 | 435 | 20.64 | 1.72 | 147.1 | 0.057 | RT |
| S-12 | 0.190 0.175 | 0.237 | 0.0433 | 427 | 18.48 | 1.54 | 148.8 | 0.079 | RT |

TABLE XXXIII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|----------------|--------|--------|-----|--------|--------|---------|-------|------------|
| S-16 | 0.191 0.179 | 0.254 | 0.0470 | 430 | 22.56 | 1.88 | 145.7 | 0.062 | RT |
| S-20 | 0.187 0.180 | 0.239 | 0.0439 | 394 | 17.28 | 1.44 | 149.8 | 0.078 | RT |
| S-24 | 0.190 0.184 | 0.238 | 0.0445 | 426 | 18.96 | 1.58 | 148.4 | 0.078 | RT |
| S-28 | 0.189 0.183 | 0.240 | 0.0446 | 436 | 19.44 | 1.62 | 148.1 | 0.076 | RT |
| S-31 | 0.105 | 0.259 | 0.0272 | 401 | 10.92 | 0.910 | 155.3 | 0.056 | RT |
| S-32 | 0.106 | 0.269 | 0.0285 | 440 | 12.55 | 1.046 | 153.8 | 0.049 | RT |
| S-33 | 0.107 | 0.269 | 0.0288 | 500 | 14.39 | 1.199 | 152.2 | 0.048 | RT |
| S-34 | 0.102 | 0.263 | 0.0268 | 351 | 9.40 | 0.783 | 156.8 | 0.054 | RT |
| S-35 | 0.105 | 0.278 | 0.0292 | 489 | 14.27 | 1.189 | 152.3 | 0.039 | RT |
| S-36 | 0.106 | 0.274 | 0.0290 | 496 | 14.39 | 1.199 | 152.2 | 0.043 | RT |
| S-37 | 0.186 0.180 | 0.248 | 0.0454 | 289 | 13.10 | 1.092 | 153.3 | 0.067 | RT |
| S-38 | 0.189 0.174 | 0.247 | 0.0446 | 373 | 16.64 | 1.387 | 150.3 | 0.070 | RT |
| S-39 | 0.190 0.175 | 0.237 | 0.0433 | 393 | 17.02 | 1.418 | 150.0 | 0.080 | RT |
| S-40 | 0.185 0.177 | 0.215 | 0.0389 | 247 | 9.60 | 0.800 | 156.6 | 0.100 | RT |
| S-41 | 0.189 0.182 | 0.238 | 0.0441 | 302 | 13.33 | 1.111 | 153.1 | 0.078 | RT |
| S-42 | 0.190 0.181 | 0.211 | 0.0391 | 290 | 11.34 | 0.945 | 154.9 | 0.105 | RT |
| S-43 | 0.106 | 0.078 | 0.0083 | 171 | 1.416 | 0.138 | 166.6 | 0.238 | RT |
| S-44 | 0.107 | 0.280 | 0.0300 | 360 | 10.81 | 0.901 | 155.4 | 0.038 | RT |
| S-45 | 0.107 | 0.262 | 0.0280 | 371 | 10.40 | 0.867 | 155.8 | 0.055 | RT |
| S-46 | 0.103 | 0.275 | 0.0283 | 336 | 9.50 | 0.792 | 156.7 | 0.042 | RT |
| S-47 | 0.105 | 0.243 | 0.0255 | 342 | 8.72 | 0.727 | 157.5 | 0.072 | RT |

TABLE XXXIII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|----------------|--------|--------|------|--------|--------|---------|-------|------------|
| S-48 | 0.104 | 0.271 | 0.0282 | 351 | 9.89 | 0.824 | 156.3 | 0.045 | RT |
| S-50 | 0.193 0.188 | 0.247 | 0.0471 | 361 | 17.02 | 1.418 | 150.0 | 0.069 | RT |
| S-54 | 0.194 0.179 | 0.233 | 0.0435 | 278 | 12.11 | 1.009 | 154.2 | 0.082 | RT |
| S-58 | 0.193 0.181 | 0.187 | 0.0350 | 269 | 9.40 | 0.783 | 156.8 | 0.128 | RT |
| S-62 | 0.194 0.186 | 0.245 | 0.0466 | 464 | 21.60 | 1.80 | 146.4 | 0.067 | RT |
| S-66 | 0.194 0.185 | 0.240 | 0.0455 | 475 | 21.60 | 1.80 | 146.4 | 0.077 | RT |
| S-70 | 0.194 0.187 | 0.248 | 0.0472 | 435 | 20.52 | 1.71 | 147.2 | 0.071 | RT |
| S-73 | 0.116 | 0.267 | 0.0310 | 491 | 15.22 | 1.268 | 151.5 | 0.051 | RT |
| S-74 | 0.118 | 0.272 | 0.0321 | 583 | 18.72 | 1.56 | 148.6 | 0.043 | RT |
| S-75 | 0.118 | 0.264 | 0.0316 | 577 | 18.24 | 1.52 | 149.0 | 0.054 | RT |
| S-76 | 0.113 | 0.269 | 0.0304 | 766 | 23.28 | 1.94 | 145.2 | 0.050 | RT |
| S-77 | 0.113 | 0.274 | 0.0310 | 770 | 23.88 | 1.99 | 144.8 | 0.046 | RT |
| S-78 | 0.114 | 0.273 | 0.0311 | 722 | 22.44 | 1.87 | 145.8 | 0.046 | RT |
| S-79 | 0.104 | 0.247 | 0.0257 | 546* | 14.04 | 1.170 | 152.5 | 0.073 | RT |
| S-80 | 0.105 | 0.274 | 0.0288 | 613* | 17.64 | 1.47 | 149.5 | 0.046 | RT |
| S-81 | 0.105 | 0.272 | 0.0286 | 646* | 18.48 | 1.54 | 148.8 | 0.044 | RT |
| S-82 | 0.105 | 0.264 | 0.0277 | 481* | 13.33 | 1.111 | 153.1 | 0.053 | RT |
| S-83 | 0.105 | 0.272 | 0.0286 | 361* | 13.92 | 1.160 | 152.6 | 0.046 | RT |
| S-84 | 0.105 | 0.264 | 0.0277 | 507* | 14.04 | 1.170 | 152.5 | 0.054 | RT |
| | | | | | | | | | |
| | | | | | | | | | |

*Crack propagating in the chamber hoop-direction.

TABLE XXXIII (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C. D. | Test Temp. |
|--------------|----------------|----------|--------|-----|----------|----------|---------|-------|------------|
| S-9 | 0.188 0.176 | 0.253 | 0.0460 | 683 | 31.44 | 2.62 | 140.0 | 0.064 | 200°F |
| S-13 | 0.188 0.175 | 0.237 | 0.0430 | 647 | 27.84 | 2.32 | 142.3 | 0.080 | 200°F |
| S-17 | 0.192 0.179 | 0.260 | 0.0482 | 528 | 25.44 | 2.12 | 143.8 | 0.055 | 200°F |
| S-21 | 0.189 0.176 | 0.232 | 0.0423 | 522 | 22.08 | 1.84 | 146.0 | 0.084 | 200°F |
| S-25 | 0.190 0.185 | 0.239 | 0.0448 | 549 | 24.60 | 2.05 | 144.3 | 0.075 | 200°F |
| S-29 | 0.189 0.179 | 0.250 | 0.0460 | 592 | 27.24 | 2.27 | 142.6 | 0.065 | 200°F |
| S-51 | 0.192 0.187 | 0.241 | 0.0457 | 473 | 21.60 | 1.80 | 146.4 | 0.074 | 200°F |
| S-55 | 0.187 0.177 | 0.314 | 0.0571 | 691 | 39.48 | 3.29 | 135.3 | | 200°F |
| S-59 | 0.193 0.182 | 0.195 | 0.0366 | 331 | 12.11 | 1.009 | 154.2 | 0.120 | 200°F |
| S-63 | 0.194 0.187 | 0.256 | 0.0488 | 642 | 31.32 | 2.61 | 140.1 | 0.062 | 200°F |
| S-67 | 0.193 0.185 | 0.261 | 0.0493 | 677 | 33.36 | 2.78 | 138.9 | 0.055 | 200°F |
| S-71 | 0.194 0.187 | 0.256 | 0.0488 | 625 | 30.48 | 2.54 | 140.6 | 0.060 | 200°F |
| | | | | | | | | | |
| S-10 | 0.188 0.175 | 0.258 | 0.0468 | 928 | 43.44 | 3.62 | 133.2 | 0.063 | 320°F |
| S-14 | 0.188 0.176 | 0.243 | 0.0442 | 839 | 37.08 | 3.09 | 136.7 | 0.076 | 320°F |
| S-18 | 0.192 0.181 | 0.255 | 0.0476 | 850 | 40.44 | 3.37 | 134.8 | 0.063 | 320°F |
| S-22 | 0.190 0.183 | 0.234 | 0.0436 | 820 | 35.76 | 2.98 | 137.5 | 0.082 | 320°F |
| S-26 | 0.190 0.184 | 0.245 | 0.0458 | 846 | 38.76 | 3.23 | 135.8 | 0.072 | 320°F |
| S-30 | 0.188 0.179 | 0.247 | 0.0453 | 917 | 41.52 | 3.46 | 134.2 | 0.071 | 320°F |
| S-52 | 0.191 0.185 | 0.248 | 0.0466 | 579 | 27.00 | 2.25 | 142.8 | 0.069 | 320°F |
| S-56 | 0.193 0.183 | 0.239 | 0.0449 | 516 | 23.16 | 1.93 | 145.3 | 0.077 | 320°F |

TABLE XXXIII (cont.)

[illegible]

TABLE XXXIV

PRECRACK CHARPY IMPACT DATA - 6Al-4V TITANIUM

| <u>Minuteman Chamber S/N</u> | <u>Component</u> | <u>Specimen Location</u> | <u>Wall Thickness</u> | <u>Test Temperature, °F</u> | | |
|----------------------------------|------------------|------------------------------|---------------------------|-----------------------------|-------------------------|---------------------------|
| | | | | <u>-40</u> | <u>RT</u> | <u>200</u> |
| 673078 | Fwd Closure | 2-in. fwd of G1 weld | 0.108 | | 563 - 704 Avg(3) 645 | 320 |
| | | G1 reinforced section | 0.173 | 318 - 324 Avg(3) 320 | 374 - 414 Avg(3) 397 | 640 - 715 Avg(2) 678 |
| | | G1 reinforced section | 0.172 | 368 - 435 Avg(2) 401 | 530 - 564 Avg(3) 543 | 631 - 710 Avg(2) 670 |
| | Fwd Cyl | 2-in. aft of G1 weld | 0.101 | | 518 - 701 Avg(3) 630 | |
| | | 2-in. fwd of G2 weld | 0.097 | | 655 - 824 Avg(3) 727 | |
| | | G2 reinforced section | 0.172 | | 442 - 738 Avg(3) 617 | |
| | Aft Cyl | G2 reinforced section | 0.168 | | 422 - 482 Avg(3) 456 | |
| | | 2-in. aft of G2 weld | 0.100 | | 446 - 494 Avg(3) 476 | |
| | | 2-in. fwd of G3 weld | 0.098 | | 555 - 643 Avg(3) 608 | |
| | | G3 reinforced section | 0.167 | 343 - 404 Avg(3) 380 | 462 - 512 Avg(3) 484 | 676 - 815 Avg(3) 733 |
| | | G3 reinforced section | 0.176 | 398 - 488 Avg(3) 456 | 603 - 827 Avg(3) 706 | 862 - 990 Avg(3) 908 |
| | Aft Closure | | | | | 895 - 1081 Avg(3) 994 |
| | | | | | | 908 - 1174 Avg(3) 1061 |

TABLE XXXIV

| <u>Minuteman Chamber S/N</u> | <u>Component</u> | <u>Specimen Location</u> | <u>Wall Thickness</u> | <u>Test Temperature, °F</u> | | |
|----------------------------------|----------------------------|--|---------------------------|-----------------------------|-------------------------|-----|
| | | | | -40 | RT | 200 |
| 673078 | Aft Closure (continued) | 2-in. aft of G3 weld | 0.106 | | 570 - 650 Avg(3) 622 | 320 |
| | | Near secondary hoop-direction fracture | 0.108 | | 567 - 642 Avg(3) 614 | |
| | | Ditto | 0.105 | | 492 - 539 Avg(3) 519 | |

TABLE XXXV

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER 673078 (14 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|-----------------------|
| Forward Dome | - |
| Forward Adaptor | E1 - 14 |
| Forward Cylinder | |
| At G1 Weld | E16 - 30 |
| At G2 Weld | E31 - 36 |
| Aft Cylinder | |
| At G2 Weld | E37 - 42 |
| At G3 Weld | E43 - 57 |
| Aft Flange | E58 - 72 E73 - 78* |

*Specimens taken at intersection of primary fracture (axial) and secondary fracture (hoop) in aft flange.

TABLE XXXV (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|-------|--------|--------|-----|--------|--------|---------|--------|------------|
| E-5 | 0.175 | 0.271 | 0.0475 | 318 | 15.10 | 1.258 | 151.6 | 0.044 | -40°F |
| E-13 | 0.175 | 0.249 | 0.0437 | 318 | 13.92 | 1.160 | 152.6 | 0.065 | -40°F |
| E-17 | 0.175 | 0.277 | 0.0485 | 435 | 21.12 | 1.6 | 146.7 | 0.038 | -40°F |
| E-21 | 0.171 | 0.264 | 0.0452 | 368 | 16.64 | 1.387 | 150.3 | 0.051 | -40°F |
| E-25 | 0.173 | 0.178 | 0.0308 | 271 | 8.36 | 0.697 | 157.9 | 0.136 | -40°F |
| E-59 | 0.177 | 0.268 | 0.0475 | 488 | 23.16 | 1.93 | 145.3 | 0.047 | -40°F |
| E-63 | 0.178 | 0.273 | 0.0487 | 483 | 23.52 | 1.96 | 145.0 | 0.042 | -40°F |
| E-67 | 0.178 | 0.267 | 0.0476 | 398 | 18.96 | 1.58 | 148.4 | 0.048 | -40°F |
| | | | | | | | | | |
| E-8 | 0.175 | 0.248 | 0.0435 | 403 | 17.52 | 1.46 | 149.6 | 0.0636 | RT |
| E-12 | 0.174 | 0.257 | 0.0448 | 374 | 16.78 | 1.398 | 150.2 | 0.0604 | RT |
| E-20 | 0.171 | 0.270 | 0.0462 | 530 | 24.48 | 2.04 | 144.4 | 0.0448 | RT |
| | | | | | | | | | |
| E-9 | 0.174 | 0.2169 | 0.0377 | 324 | 12.228 | 1.019 | 154.1 | | -40°F |
| E-47 | 0.167 | 0.2376 | 0.0397 | 404 | 16.056 | 1.338 | 150.8 | | -40°F |
| E-51 | 0.171 | 0.2191 | 0.0375 | 343 | 12.876 | 1.073 | 153.5 | | -40°F |
| E-55 | 0.169 | 0.2271 | 0.0384 | 393 | 15.096 | 1.258 | 151.6 | | -40°F |
| | | | | | | | | | |
| E-1 | 0.108 | 0.2560 | 0.0276 | 704 | 19.44 | 1.62 | 148.1 | | RT |
| E-2 | 0.108 | 0.2462 | 0.0266 | 543 | 14.976 | 1.248 | 151.7 | | RT |
| E-3 | 0.108 | 0.2495 | 0.0269 | 669 | 18.00 | 1.50 | 149.2 | | RT |

TABLE XXXV (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C. D. | Test Temp. |
|--------------|-------|----------|--------|-----|----------|----------|---------|-------|------------|
| E-4 | 0.173 | 0.2296 | 0.0397 | 414 | 16.416 | 1.368 | 150.5 | | RT |
| E-16 | 0.172 | 0.2544 | 0.0438 | 564 | 24.72 | 2.06 | 144.2 | | RT |
| E-28 | 0.102 | 0.2679 | 0.0273 | 701 | 19.14 | 1.595 | 148.3 | | RT |
| E-29 | 0.101 | 0.2525 | 0.0255 | 518 | 13.212 | 1.101 | 153.2 | | RT |
| E-30 | 0.100 | 0.2394 | 0.0239 | 672 | 16.056 | 1.338 | 150.8 | | RT |
| E-31 | 0.097 | 0.2619 | 0.0254 | 655 | 16.644 | 1.387 | 150.3 | | RT |
| E-32 | 0.097 | 0.2700 | 0.0262 | 824 | 21.60 | 1.80 | 146.4 | | RT |
| E-33 | 0.098 | 0.2610 | 0.0256 | 703 | 18.00 | 1.50 | 149.2 | | RT |
| E-35 | 0.172 | 0.2692 | 0.0463 | 671 | 31.08 | 2.59 | 140.2 | | RT |
| E-37 | 0.167 | 0.2162 | 0.0361 | 482 | 17.40 | 1.45 | 149.1 | | RT |
| E-38 | 0.168 | 0.2009 | 0.0338 | 422 | 14.268 | 1.189 | 152.3 | | RT |
| E-39 | 0.171 | 0.2563 | 0.0438 | 464 | 20.34 | 1.695 | 147.3 | | RT |
| E-40 | 0.100 | 0.2428 | 0.0243 | 494 | 12.00 | 1.000 | 154.3 | | RT |
| E-41 | 0.100 | 0.2469 | 0.0247 | 446 | 11.028 | 0.919 | 155.2 | | RT |
| E-42 | 0.100 | 0.2458 | 0.0246 | 488 | 12.00 | 1.000 | 154.3 | | RT |
| E-43 | 0.097 | 0.2654 | 0.0257 | 643 | 16.536 | 1.378 | 150.4 | | RT |
| E-44 | 0.098 | 0.2566 | 0.0251 | 625 | 15.696 | 1.308 | 151.1 | | RT |
| E-45 | 0.098 | 0.2350 | 0.0230 | 555 | 12.768 | 1.064 | 153.6 | | RT |
| E-46 | 0.166 | 0.2503 | 0.0415 | 512 | 21.24 | 1.77 | 146.6 | | RT |
| E-54 | 0.168 | 0.2261 | 0.0380 | 477 | 18.12 | 1.51 | 149.1 | | RT |
| E-58 | 0.174 | 0.2419 | 0.0421 | 687 | 28.92 | 2.41 | 141.6 | | RT |

TABLE XXXV (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C-D | Test Temp. |
|--------------|-------|--------|--------|-------|--------|--------|---------|--------|------------|
| E-70 | 0.106 | 0.2510 | 0.0266 | 650 | 17.28 | 1.44 | 149.8 | | RT |
| E-71 | 0.107 | 0.2508 | 0.0268 | 645 | 17.28 | 1.44 | 149.8 | | RT |
| E-72 | 0.106 | 0.2501 | 0.0265 | 570 | 15.096 | 1.258 | 151.6 | | RT |
| E-73 | 0.108 | 0.2605 | 0.0281 | 632 | 17.76 | 1.48 | 149.4 | | RT |
| E-74 | 0.108 | 0.2511 | 0.0271 | 642 | 17.40 | 1.45 | 149.7 | | RT |
| E-75 | 0.107 | 0.2445 | 0.0262 | 567 | 14.856 | 1.238 | 151.8 | | RT |
| E-76 | 0.105 | 0.2587 | 0.0272 | 525 * | 14.268 | 1.189 | 152.3 | | RT |
| E-77 | 0.105 | 0.2510 | 0.0264 | 492 * | 12.996 | 1.083 | 153.4 | | RT |
| E-78 | 0.105 | 0.2437 | 0.0256 | 539 * | 13.80 | 1.150 | 152.7 | | RT |
| E-24 | 0.122 | 0.270 | 0.0465 | 534 | 24.84 | 2.07 | 144.1 | 0.0436 | RT |
| E-34 | 0.174 | 0.276 | 0.0481 | 738 | 35.52 | 2.96 | 137.6 | 0.0364 | RT |
| E-36 | 0.173 | 0.237 | 0.0410 | 442 | 18.12 | 1.51 | 149.1 | 0.0766 | RT |
| E-50 | 0.172 | 0.258 | 0.0444 | 462 | 20.52 | 1.71 | 147.2 | 0.0557 | RT |
| E-62 | 0.177 | 0.298 | 0.0528 | 827 | 43.68 | 3.64 | 133.0 | 0.0197 | RT |
| E-66 | 0.177 | 0.255 | 0.0452 | 603 | 27.24 | 2.27 | 142.6 | 0.0502 | RT |
| | | | | | | | | | |
| E-6 | 0.176 | 0.266 | 0.0468 | 712 | 33.48 | 2.79 | 138.8 | 0.0496 | 200°F |
| E-10 | 0.172 | 0.254 | 0.0437 | 640 | 27.96 | 2.33 | 142.2 | 0.0625 | 200°F |
| E-18 | 0.177 | 0.250 | 0.0443 | 631 | 27.96 | 2.33 | 142.2 | 0.0622 | 200°F |
| E-22 | 0.171 | 0.252 | 0.0431 | 710 | 30.60 | 2.55 | 140.5 | 0.0630 | 200°F |
| E-52 | 0.173 | 0.273 | 0.0472 | 719 | 33.96 | 2.83 | 138.5 | 0.0417 | 200°F |

*Crack propagating in the chamber hoop-direction.

TABLE XXXV (cont.)

| SPECIMEN NO | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|-------------|-------|--------|--------|------|--------|--------|---------|--------|------------|
| E-56 | 0.174 | 0.257 | 0.0448 | 676 | 30.30 | 2.525 | 140.7 | 0.0598 | 200°F |
| E-64 | 0.177 | 0.258 | 0.0457 | 873 | 39.90 | 3.325 | 135.1 | 0.0541 | 200°F |
| E-48 | 0.166 | 0.2640 | 0.0438 | 815 | 35.70 | 2.975 | 137.5 | | 200°F |
| E-60 | 0.176 | 0.2564 | 0.0451 | 990 | 44.64 | 3.72 | 132.5 | | 200°F |
| E-68 | 0.175 | 0.2406 | 0.0421 | 862 | 36.30 | 3.025 | 137.1 | | 200°F |
| | | | | | | | | | |
| E-7 | 0.174 | 0.267 | 0.0464 | 998 | 46.32 | 3.86 | 131.6 | 0.051 | 320°F |
| E-11 | 0.173 | 0.277 | 0.0479 | 902 | 43.20 | 3.60 | 133.3 | 0.041 | 320°F |
| E-14 | 0.179 | 0.254 | 0.0455 | 916 | 41.70 | 3.475 | 134.1 | 0.063 | 320°F |
| E-19 | 0.173 | 0.284 | 0.0491 | 1230 | 60.60 | 5.05 | 124.2 | 0.033 | 320°F |
| E-23 | 0.171 | 0.287 | 0.0491 | 1050 | 51.41 | 4.284 | 128.6 | 0.033 | 320°F |
| E-26 | 0.172 | 0.228 | 0.0392 | 784 | 30.72 | 2.56 | 140.4 | 0.090 | 320°F |
| E-57 | 0.173 | 0.274 | 0.0474 | 895 | 42.42 | 3.535 | 133.7 | 0.044 | 320°F |
| E-65 | 0.175 | 0.285 | 0.0499 | 1100 | 55.18 | 4.598 | 126.7 | 0.031 | 320°F |
| E-69 | 0.175 | 0.285 | 0.0499 | 908 | 45.30 | 3.775 | 132.1 | 0.031 | 320°F |
| E-49 | 0.169 | 0.2443 | 0.0413 | 1081 | 44.64 | 3.72 | 132.5 | | 320°F |
| E-53 | 0.169 | 0.2458 | 0.0415 | 1005 | 41.70 | 3.475 | 134.1 | | 320°F |
| E-61 | 0.176 | 0.2597 | 0.0457 | 1174 | 53.64 | 4.47 | 127.5 | | 320°F |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

TABLE XXXVI

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| Minuteman S/N | Chamber Component | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|------------------|----------------------|--------------------------|-------------------|-------------------------|-------------------------|---------------------------|
| | | | | -40 | RT | 200 |
| 673095 | Fwd Closure | 2-in fwd of G1 weld | 0.106 | | 476 - 613 Avg(3) 529 | 320 |
| | | G1 reinforced section | 0.174 | 331 - 413 Avg(3) 376 | 484 - 650 Avg(3) 546 | 589 - 685 Avg(3) 635 |
| | | | | | | 908 - 1424 Avg(2) 1166 |
| | Fwd Cyl | G1 reinforced section | 0.175 | 225 - 393 Avg(3) 328 | 543 - 674 Avg(3) 603 | 708 - 769 Avg(3) 749 |
| | | 2-in. aft of G1 weld | 0.101 | | 608 - 783 Avg(3) 684 | 837 - 1030 Avg(3) 919 |
| | | 2-in. fwd of G2 weld | 0.101 | | 452 - 677 Avg(3) 598 | |
| | | G2 reinforced section | 0.178 | | 541 - 696 Avg(3) 634 | |
| | | G2 reinforced section | 0.174 | | 352 - 444 Avg(3) 386 | |
| | | 2-in. aft of G2 weld | 0.102 | | 334 - 401 Avg(4) 379 | |
| | | Ditto Hoop | 0.102 | | 280 - 325 Avg(3) 301 | |
| | | 2-in. fwd of G3 weld | 0.099 | | 355 - 419 Avg(3) 389 | |
| | | G3 reinforced section | 0.179 | 208 - 253 Avg(3) 336 | 352 - 392 Avg(3) 375 | 532 - 577 Avg(3) 559 |
| | Aft Closure | G3 reinforced section | 0.164 | 252 - 266 Avg(2) 259 | 351 - 400 Avg(3) 377 | 752 - 1038 Avg(3) 850 |
| | | 2-in. aft of G3 weld | 0.103 | | 470 - 576 Avg(3) 538 | 761 - 765 Avg(2) 763 |
| | | | | | 418 - 498 Avg(3) 458 | |

TABLE XXXVII

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER 673095 (44 IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Dome | - |
| Forward Adapter | F1 - 15 |
| Forward Cylinder | |
| At G1 Weld | F16 - 30 |
| At G2 Weld | F31 - 36 |
| Aft Cylinder | |
| At G2 Weld | F37 - 46 |
| At G3 Weld | F47 - 61 |
| Aft Flange | F62 - 76 |

TABLE XXXVII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|-------|--------|--------|-----|--------|--------|---------|-------|------------|
| F-4 | 0.172 | 0.234 | 0.0403 | 413 | 16.63 | 1.387 | 150.3 | 0.082 | -40°F |
| F-8 | 0.174 | 0.235 | 0.0410 | 383 | 15.70 | 1.308 | 151.1 | 0.080 | -40°F |
| F-12 | 0.176 | 0.231 | 0.0407 | 331 | 13.46 | 1.121 | 153.0 | 0.086 | -40°F |
| F-16 | 0.174 | 0.220 | 0.0383 | 225 | 8.63 | 0.720 | 157.5 | 0.091 | -40°F |
| F-20 | 0.175 | 0.237 | 0.0415 | 393 | 16.30 | 1.358 | 150.6 | 0.073 | -40°F |
| F-24 | 0.175 | 0.255 | 0.0447 | 365 | 16.30 | 1.358 | 150.6 | 0.062 | -40°F |
| F-50 | 0.174 | 0.276 | 0.0486 | 247 | 12.00 | 1.000 | 154.3 | 0.040 | -40°F |
| F-54 | 0.178 | 0.055 | 0.0098 | 253 | 2.48 | 0.207 | 165.3 | 0.262 | -40°F |
| F-58 | 0.179 | 0.218 | 0.0390 | 208 | 8.10 | 0.675 | 158.2 | 0.095 | -40°F |
| F-62 | 0.153 | 0.244 | 0.0379 | 266 | 10.10 | 0.841 | 156.1 | 0.070 | -40°F |
| F-66 | 0.168 | 0.315 | 0.0530 | 313 | 1.66 | 0.138 | 166.6 | | -40°F |
| F-70 | 0.165 | 0.238 | 0.0393 | 252 | 9.89 | 0.824 | 156.3 | 0.077 | -40°F |
| | | | | | | | | | |
| F-1 | 0.106 | 0.222 | 0.0235 | 497 | 14.04 | 1.170 | 152.5 | 0.095 | RT |
| F-2 | 0.106 | 0.240 | 0.0254 | 613 | 15.58 | 1.298 | 151.2 | 0.075 | RT |
| F-3 | 0.106 | 0.278 | 0.0295 | 476 | 14.04 | 1.170 | 152.5 | 0.038 | RT |
| F-5 | 0.172 | 0.262 | 0.0451 | 484 | 21.84 | 1.82 | 146.2 | 0.051 | RT |
| F-9 | 0.172 | 0.288 | 0.0496 | 650 | 32.22 | 2.685 | 139.5 | 0.024 | RT |
| F-13 | 0.175 | 0.262 | 0.0459 | 504 | 23.15 | 1.93 | 145.3 | 0.054 | RT |
| F-17 | 0.174 | 0.253 | 0.0440 | 543 | 23.88 | 1.90 | 144.8 | 0.064 | RT |
| F-21 | 0.176 | 0.285 | 0.0502 | 674 | 33.84 | 2.82 | 138.6 | 0.034 | RT |

TABLE XXXVII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|-------|--------|--------|-------|--------|--------|---------|--------|------------|
| F-25 | 0.176 | 0.268 | 0.0472 | 592 | 27.96 | 2.33 | 142.2 | 0.050 | RT |
| F-28 | 0.101 | 0.259 | 0.0262 | 608 | 15.94 | 1.328 | 150.9 | 0.056 | RT |
| F-29 | 0.101 | 0.276 | 0.0279 | 662 | 18.48 | 1.54 | 148.8 | 0.039 | RT |
| F-30 | 0.101 | 0.279 | 0.0282 | 783 | 22.08 | 1.84 | 146.0 | 0.037 | RT |
| F-31 | 0.099 | 0.246 | 0.0244 | 452 | 11.03 | 0.919 | 155.2 | 0.069 | RT |
| F-32 | 0.101 | 0.289 | 0.0292 | 666 | 19.44 | 1.62 | 148.1 | 0.026 | RT |
| F-33 | 0.102 | 0.224 | 0.0218 | 677 | 14.75 | 1.229 | 151.9 | 0.090 | RT |
| F-34 | 0.178 | 0.254 | 0.0452 | 666 | 30.12 | 2.51 | 140.8 | 0.064 | RT |
| F-35 | 0.178 | 0.229 | 0.0408 | 541 | 22.08 | 1.84 | 146.0 | 0.039 | RT |
| F-36 | 0.178 | 0.288 | 0.0513 | 696 | 35.70 | 2.975 | 137.5 | 0.030 | RT |
| F-37 | 0.172 | 0.263 | 0.0453 | 352 | 15.94 | 1.328 | 150.9 | 0.052 | RT |
| F-38 | 0.176 | 0.278 | 0.0489 | 444 | 21.72 | 1.81 | 146.3 | 0.041 | RT |
| F-39 | 0.174 | 0.266 | 0.0463 | 362 | 16.78 | 1.398 | 150.2 | 0.054 | RT |
| F-40 | 0.103 | 0.271 | 0.0280 | 401 | 11.23 | 0.936 | 155.0 | 0.042 | RT |
| F-41 | 0.101 | 0.265 | 0.0268 | 384 | 10.30 | 0.858 | 155.9 | 0.051 | RT |
| F-42 | 0.101 | 0.256 | 0.0248 | 334 | 8.28 | 0.690 | 158.0 | 0.059 | RT |
| F-43 | 0.097 | 0.257 | 0.0250 | 396 | 9.89 | 0.824 | 156.3 | 0.058 | RT |
| F-44 | 0.102 | 0.254 | 0.0260 | 299 * | 7.78 | 0.648 | 158.6 | 0.061 | RT |
| F-45 | 0.102 | 0.235 | 0.0240 | 280 * | 6.71 | 0.559 | 159.8 | 0.082 | RT |
| F-46 | 0.102 | 0.244 | 0.0249 | 325 * | 8.10 | 0.675 | 158.2 | 0.710 | RT |
| F-47 | 0.099 | 0.253 | 0.0251 | 355 | 8.92 | 0.743 | 157.3 | 0.0610 | RT |

*Crack propagating in the chamber hoop-direction.

TABLE XXXVII (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C D. | Test Temp. |
|--------------|-------|----------|--------|-----|----------|----------|---------|--------|------------|
| F-48 | 0.099 | 0.284 | 0.0281 | 419 | 11.77 | 0.981 | 154.5 | 0.033 | RT |
| F-49 | 0.098 | 0.278 | 0.0273 | 392 | 10.70 | 0.892 | 155.5 | 0.0346 | RT |
| F-51 | 0.176 | 0.249 | 0.0439 | 352 | 15.46 | 1.288 | 151.3 | 0.0634 | RT |
| F-55 | 0.179 | 0.249 | 0.0446 | 382 | 17.02 | 1.418 | 150.0 | 0.050 | RT |
| F-59 | 0.179 | 0.265 | 0.0475 | 392 | 18.60 | 1.55 | 148.7 | 0.0513 | RT |
| F-63 | 0.156 | 0.260 | 0.0406 | 351 | 14.27 | 1.189 | 152.3 | 0.057 | RT |
| F-67 | 0.171 | 0.261 | 0.0447 | 400 | 17.87 | 1.49 | 149.3 | 0.0519 | RT |
| F-71 | 0.165 | 0.248 | 0.0409 | 381 | 15.58 | 1.298 | 151.2 | 0.070 | RT |
| F-74 | 0.102 | 0.265 | 0.0270 | 498 | 13.45 | 1.121 | 153.0 | 0.0518 | RT |
| F-75 | 0.103 | 0.256 | 0.0264 | 459 | 12.11 | 1.009 | 154.2 | 0.0592 | RT |
| F-76 | 0.104 | 0.234 | 0.0244 | 418 | 10.19 | 0.849 | 156.0 | 0.0795 | RT |
| | | | | | | | | | |
| F-6 | 0.174 | 0.256 | 0.0445 | 685 | 30.48 | 2.54 | 140.6 | 0.0632 | 200°F |
| F-10 | 0.170 | 0.228 | 0.0388 | 589 | 22.86 | 1.905 | 145.5 | 0.0905 | 200°F |
| F-14 | 0.176 | 0.271 | 0.0477 | 631 | 30.12 | 2.51 | 140.8 | 0.0504 | 200°F |
| F-18 | 0.176 | 0.237 | 0.0417 | 708 | 29.52 | 2.46 | 141.2 | 0.0817 | 200°F |
| F-22 | 0.176 | 0.259 | 0.0457 | 769 | 35.16 | 2.93 | 137.8 | 0.0589 | 200°F |
| F-26 | 0.176 | 0.280 | 0.0493 | 769 | 37.92 | 3.16 | 136.2 | 0.0374 | 200°F |
| F-52 | 0.177 | 0.261 | 0.0462 | 532 | 24.60 | 2.05 | 144.3 | 0.0579 | 200°F |
| F-56 | 0.178 | 0.276 | 0.0492 | 568 | 27.96 | 2.33 | 142.2 | 0.0399 | 200°F |
| F-60 | 0.179 | 0.246 | 0.0441 | 577 | 25.44 | 2.12 | 143.8 | 0.0688 | 200°F |

TABLE XXXVII (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D. | Test Temp. |
|--------------|-------|----------|--------|------|--------|--------|---------|--------|------------|
| F-64 | 0.158 | 0.224 | 0.0354 | 470 | 16.64 | 1.387 | 150.3 | 0.0933 | 200°F |
| F-68 | 0.169 | 0.268 | 0.0453 | 576 | 26.10 | 2.175 | 143.3 | 0.0475 | 200°F |
| F-72 | 0.167 | 0.258 | 0.0431 | 568 | 24.48 | 2.04 | 144.4 | 0.0632 | 200°F |
| | | | | | | | | | |
| F-7 | 0.173 | 0.260 | 0.0450 | 1424 | 51.41 | 4.284 | 128.6 | 0.060 | 320°F |
| F-11 | 0.172 | 0.288 | 0.0495 | 908 | 44.94 | 3.745 | 132.3 | 0.028 | 320°F |
| F-15 | 0.175 | 0.113 | 0.0198 | 606 | 12.00 | 1.000 | 154.3 | 0.200 | 320°F |
| F-19 | 0.176 | 0.197 | 0.0347 | 837 | 29.04 | 2.42 | 141.5 | 0.121 | 320°F |
| F-23 | 0.177 | 0.262 | 0.0464 | 891 | 41.34 | 3.445 | 134.3 | 0.056 | 320°F |
| F-27 | 0.178 | 0.268 | 0.0477 | 1030 | 49.14 | 4.095 | 130.1 | 0.049 | 320°F |
| F-53 | 0.178 | 0.279 | 0.0497 | 752 | 37.38 | 3.115 | 136.5 | 0.039 | 320°F |
| F-57 | 0.178 | 0.274 | 0.0488 | 759 | 37.02 | 3.085 | 136.7 | 0.047 | 320°F |
| F-61 | 0.178 | 0.264 | 0.0470 | 1038 | 48.78 | 4.065 | 130.3 | 0.052 | 320°F |
| F-65 | 0.164 | 0.086 | 0.0141 | 445 | 6.28 | 0.523 | 160.3 | 0.232 | 320°F |
| F-69 | 0.166 | 0.261 | 0.0433 | 765 | 33.12 | 2.76 | 139.0 | 0.060 | 320°F |
| F-73 | 0.167 | 0.277 | 0.0462 | 761 | 35.16 | 2.93 | 137.8 | 0.039 | 320°F |
| | | | | | | | | | |
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| | | | | | | | | | |
| | | | | | | | | | |

TABLE XXVIII

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| <u>Minuteman Chamber S/N</u> | <u>Component</u> | <u>Specimen Location</u> | <u>Wall Thickness</u> | <u>Test Temperature, °F</u> | |
|----------------------------------|------------------|------------------------------|---------------------------|-----------------------------|----------------------------|
| | | | | <u>-40</u> | <u>RT</u> |
| 673122 | Fwd Closure | 2-in. fwd of G1 weld | 0.102 | | 532 - 631 Avg(3) 573 |
| | | G1 reinforced section | 0.177 | 280 - 452 Avg(3) 375 | 656 - 693 Avg(3) 679 |
| | | G1 reinforced section | 0.171 | | 334 - 578 Avg(3) 439 |
| | Pwd Cyl | 2-in. Aft of G1 weld | 0.102 | | 396 - 412 Avg(3) 406 |
| | | 2-in. fwd of G2 weld | 0.100 | | 498 - 588 Avg(3) 549 |
| | | G2 reinforced section | 0.170 | 352 - 359 Avg(3) 355 | 408 - 554 Avg(3) 484 |
| | Aft Cyl | G2 reinforced section | 0.171 | 378 - 464 Avg(3) 409 | 593 - 634 Avg(3) 619 |
| | | 2-in. aft of G2 weld | 0.097 | | 550 - 620 Avg(3) 585 |
| | | 2-in. fwd of G3 weld | 0.094 | | 441 - 548 Avg(3) 484 |
| | Aft Closure | G3 reinforced section | 0.170 | | 387 - 631 Avg(3) 507 |
| | | G3 reinforced section | 0.179 | 169 - 468 Avg(3) 329 | 601 - 640 Avg(3) 624 |
| | | 2-in. aft of G3 weld | 0.106 | | 487 - 519 Avg(3) 503 |
| | | | | | 770 - 1060 Avg(3) 874 |
| | | | | | 1140 - 1200 Avg(3) 1163 |
| | | | | | 1250 - 1340 Avg(3) 1293 |
| | | | | | 289 - 875 Avg(3) 638 |
| | | | | | 1080 - 1330 Avg(3) 1167 |
| | | | | | 719 - 865 Avg(3) 815 |
| | | | | | 1130 - 1300 Avg(3) 1200 |
| | | | | | |
| | | | | | |

TABLE XXXIX

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER 673122 (44-IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Dome | - |
| Forward Adaptor | G1 - 15 |
| Forward Cylinder | |
| At G1 Weld | G16 - 21 |
| At G2 Weld | G22 - 36 |
| Aft Cylinder | |
| At G2 Weld | G37 - 51 |
| At G3 Weld | G52 - 57 |
| Aft Flange | G58 - 72 |

TABLE XXXIX (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D | Test Temp. |
|--------------|-------|----------|--------|-----|--------|--------|---------|--------|------------|
| G-4 | 0.177 | 0.218 | 0.0386 | 280 | 10.81 | 0.901 | 155.4 | 0.095 | -40°F |
| G-8 | 0.178 | 0.266 | 0.0474 | 392 | 18.60 | 1.55 | 148.7 | 0.049 | -40°F |
| G-12 | 0.180 | 0.261 | 0.0470 | 452 | 21.24 | 1.77 | 146.6 | 0.053 | -40°F |
| G-25 | 0.173 | 0.276 | 0.0478 | 354 | 16.90 | 1.408 | 150.1 | 0.040 | -40°F |
| G-29 | 0.170 | 0.280 | 0.0477 | 352 | 16.78 | 1.398 | 150.2 | 0.035 | -40°F |
| G-33 | 0.174 | 0.282 | 0.0491 | 359 | 17.64 | 1.47 | 149.5 | 0.034 | -40°F |
| G-37 | 0.174 | 0.272 | 0.0473 | 378 | 17.88 | 1.49 | 149.3 | 0.043 | -40°F |
| G-41 | 0.171 | 0.260 | 0.0445 | 464 | 20.64 | 1.72 | 147.1 | 0.054 | -40°F |
| G-45 | 0.171 | 0.250 | 0.0428 | 386 | 16.54 | 1.378 | 150.4 | 0.064 | -40°F |
| G-58 | 0.176 | 0.275 | 0.0490 | 169 | 8.28 | 0.690 | 158.0 | 0.042 | -40°F |
| G-62 | 0.178 | 0.278 | 0.0495 | 468 | 23.16 | 1.93 | 145.3 | 0.036 | -40°F |
| G-66 | 0.178 | 0.269 | 0.0480 | 350 | 16.78 | 1.398 | 150.2 | 0.048 | -40°F |
| | | | | | | | | | |
| G-1 | 0.102 | 0.230 | 0.0235 | 557 | 13.10 | 1.092 | 153.3 | 0.0840 | RT |
| G-2 | 0.102 | 0.289 | 0.0295 | 532 | 15.70 | 1.308 | 151.1 | 0.0265 | RT |
| G-3 | 0.103 | 0.282 | 0.0291 | 631 | 18.36 | 1.53 | 148.9 | 0.0307 | RT |
| G-5 | 0.176 | 0.252 | 0.0443 | 693 | 30.72 | 2.56 | 142.7 | 0.0594 | RT |
| G-9 | 0.176 | 0.272 | 0.0479 | 656 | 31.44 | 2.62 | 140.0 | 0.0437 | RT |
| G-13 | 0.178 | 0.254 | 0.0452 | 688 | 31.08 | 2.59 | 140.2 | 0.0622 | RT |
| G-16 | 0.172 | 0.243 | 0.0419 | 578 | 24.24 | 2.02 | 144.6 | 0.0733 | RT |
| G-17 | 0.171 | 0.260 | 0.0445 | 404 | 18.00 | 1.50 | 149.2 | 0.0551 | RT |

TABLE XXXIX (cont.)

| SPECIMEN NO | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|-------------|-------|--------|--------|-----|--------|--------|---------|--------|------------|
| G-18 | 0.170 | 0.263 | 0.0448 | 334 | 14.98 | 1.248 | 151.7 | 0.0523 | RT |
| G-19 | 0.101 | 0.271 | 0.0274 | 410 | 11.23 | 0.936 | 155.0 | 0.0439 | RT |
| G-20 | 0.103 | 0.277 | 0.0286 | 396 | 11.34 | 0.945 | 154.9 | 0.0369 | RT |
| G-21 | 0.102 | 0.265 | 0.0270 | 412 | 11.12 | 0.927 | 155.1 | 0.0504 | RT |
| G-22 | 0.100 | 0.278 | 0.0278 | 498 | 16.64 | 1.387 | 150.3 | 0.0374 | RT |
| G-23 | 0.100 | 0.288 | 0.0288 | 562 | 16.18 | 1.348 | 150.7 | 0.0277 | RT |
| G-24 | 0.101 | 0.280 | 0.0283 | 588 | 16.64 | 1.387 | 150.3 | 0.0342 | RT |
| G-26 | 0.171 | 0.256 | 0.0438 | 408 | 17.88 | 1.49 | 149.3 | 0.0582 | RT |
| G-30 | 0.170 | 0.274 | 0.0466 | 554 | 25.80 | 2.15 | 143.5 | 0.0401 | RT |
| G-34 | 0.170 | 0.277 | 0.0472 | 491 | 23.16 | 1.93 | 145.3 | 0.0402 | RT |
| G-38 | 0.172 | 0.273 | 0.0470 | 631 | 29.64 | 2.47 | 141.1 | 0.0461 | RT |
| G-42 | 0.171 | 0.269 | 0.0460 | 634 | 29.16 | 2.43 | 141.4 | 0.0457 | RT |
| G-46 | 0.169 | 0.265 | 0.0449 | 593 | 26.64 | 2.22 | 143.0 | 0.0494 | RT |
| G-49 | 0.097 | 0.278 | 0.0270 | 550 | 14.86 | 1.238 | 151.8 | 0.0381 | RT |
| G-50 | 0.097 | 0.283 | 0.0275 | 620 | 17.04 | 1.42 | 149.9 | 0.0323 | RT |
| G-51 | 0.097 | 0.282 | 0.0274 | 586 | 16.06 | 1.338 | 150.8 | 0.0372 | RT |
| G-52 | 0.093 | 0.271 | 0.0252 | 441 | 11.12 | 0.927 | 155.1 | 0.0442 | RT |
| G-53 | 0.094 | 0.272 | 0.0256 | 464 | 11.88 | 0.990 | 154.4 | 0.0433 | RT |
| G-54 | 0.095 | 0.263 | 0.0250 | 548 | 13.69 | 1.141 | 152.8 | 0.0517 | RT |
| G-55 | 0.166 | 0.273 | 0.0453 | 387 | 17.52 | 1.46 | 149.6 | 0.0426 | RT |
| G-56 | 0.170 | 0.253 | 0.0430 | 502 | 21.60 | 1.80 | 146.4 | 0.0626 | RT |

TABLE XXXIX (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in. - lb | fr - lb | DEGREES | C D. | Test Temp. |
|--------------|-------|----------|--------|------|----------|---------|---------|--------|------------|
| G-57 | 0.173 | 0.277 | 0.0480 | 631 | 30.30 | 2.525 | 140.7 | 0.0484 | RT |
| G-59 | 0.180 | 0.270 | 0.0486 | 640 | 31.08 | 2.59 | 140.2 | 0.0379 | RT |
| G-63 | 0.179 | 0.280 | 0.0502 | 631 | 31.68 | 2.64 | 139.8 | 0.0350 | RT |
| G-67 | 0.178 | 0.271 | 0.0483 | 601 | 29.04 | 2.42 | 141.5 | 0.0444 | RT |
| G-70 | 0.104 | 0.281 | 0.0293 | 487 | 14.27 | 1.189 | 152.3 | 0.0337 | RT |
| G-71 | 0.107 | 0.285 | 0.0305 | 519 | 15.82 | 1.318 | 151.0 | 0.0314 | RT |
| G-72 | 0.107 | 0.280 | 0.0300 | 503 | 15.10 | 1.258 | 151.6 | 0.0359 | RT |
| | | | | | | | | | |
| G-6 | 0.178 | 0.258 | 0.0460 | 753 | 34.62 | 2.885 | 138.1 | 0.0570 | 200°F |
| G-10 | 0.178 | 0.270 | 0.0481 | 1040 | 50.26 | 4.188 | 129.2 | 0.0448 | 200°F |
| G-14 | 0.179 | 0.281 | 0.0503 | 1100 | 55.37 | 4.614 | 126.6 | 0.0352 | 200°F |
| G-27 | 0.172 | 0.261 | 0.0449 | 750 | 33.66 | 2.805 | 138.7 | 0.0574 | 200°F |
| G-31 | 0.171 | 0.260 | 0.0445 | 289 | 12.86 | 1.073 | 153.5 | 0.0553 | 200°F |
| G-35 | 0.172 | 0.290 | 0.0499 | 875 | 43.68 | 3.64 | 133.0 | 0.0268 | 200°F |
| G-39 | 0.173 | 0.271 | 0.0469 | 862 | 40.44 | 3.37 | 134.8 | 0.0447 | 200°F |
| G-43 | 0.175 | 0.248 | 0.0434 | 865 | 37.56 | 3.13 | 136.4 | 0.0724 | 200°F |
| G-47 | 0.174 | 0.245 | 0.0427 | 719 | 30.72 | 2.56 | 140.4 | 0.0720 | 200°F |
| G-60 | 0.179 | 0.276 | 0.0495 | 770 | 38.10 | 3.175 | 136.1 | 0.0392 | 200°F |
| G-64 | 0.179 | 0.280 | 0.0502 | 791 | 39.72 | 3.31 | 135.2 | 0.0358 | 200°F |
| G-68 | 0.179 | 0.279 | 0.0500 | 1060 | 52.99 | 4.416 | 127.8 | 0.0375 | 200°F |
| | | | | | | | | | |

[illegible][illegible]

TABLE XL

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| <u>Minuteman Chamber S/N</u> | <u>Specimen Location</u> | <u>Wall Thickness</u> | <u>Test Temperature, °F</u> | | |
|----------------------------------|--|---------------------------|-----------------------------|-------------------------|-------------------------|
| | | | <u>-40</u> | <u>RT</u> | <u>320</u> |
| 674514 | Fwd Closure 2-in. fwd of G1 weld | 0.106 | | 419 - 451 Avg(3) 436 | |
| | | | 315 - 354 Avg(3) 329 | 479 - 480 Avg(2) 480 | 510 - 634 Avg(4) 549 |
| | | | | | 725 - 927 Avg(3) 857 |
| | G1 reinforced section | 0.175 | | | |
| | | | 206 - 241 Avg(3) 223 | 268 - 383 Avg(3) 309 | 344 - 451 Avg(3) 392 |
| | | | | | 606 - 784 Avg(3) 677 |
| | G1 reinforced section | 0.175 | | | |
| | | | | | |
| | | | | | |
| | 2-in. aft of G1 weld | 0.100 | | 426 - 496 Avg(3) 467 | |
| | | | | | |
| | | | | | |
| | 20-in. aft of G2 weld | 0.098 | | 295 - 324 Avg(3) 306 | |
| | | | | | |
| | | | | | |
| | Ditto Hoop | 0.098 | | 274 - 320 Avg(3) 304 | |
| | | | | | |
| | | | | | |
| | 2-in. fwd of G3 weld | 0.100 | | 302 - 362 Avg(3) 340 | |
| | | | | | |
| | | | | | |
| | G3 reinforced section | 0.170 | 244 - 381 Avg(4) 316 | 274 - 524 Avg(5) 376 | 390 - 657 Avg(4) 562 |
| | | | | | 906 - 989 Avg(2) 948 |
| | | | | | |
| | G3 reinforced section | 0.170 | 348 - 367 Avg(3) 354 | 534 - 702 Avg(3) 591 | 617 - 811 Avg(4) 714 |
| | | | | | 836 - 983 Avg(3) 907 |
| | | | | | |
| Aft Closure | 2-in. aft of G3 weld | 0.100 | | 317 - 531 Avg(3) 448 | |
| | | | | | |
| | | | | | |

TABLE XLI

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER 674514 (44-IN. DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|----------------------|
| Forward Dome | - |
| Forward Adaptor | H1 - 15 H70 - 74 |
| Forward Cylinder | |
| At G1 Weld | H16 - 30 H75 - 83 |
| At G2 Weld | - |
| Aft Cylinder | |
| At G2 Weld | H61 - 66* |
| At G3 Weld | H84 - 89 H46 - 60 |
| Aft Flange | H31 - 45 H90 - 95 |

*Specimens taken at intersection of primary fracture (axial) and secondary fracture (hoop) in aft cylinder, approx. midway between G2 and G3 welds.

TABLE XLI (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft. - lb | DEGREES | C D | Test Temp. |
|--------------|----------------|----------|--------|-----|----------|----------|---------|-------|------------|
| H-75 | 0.176 0.162 | 0.253 | 0.0428 | 206 | 8.81 | 0.734 | 157.4 | 0.065 | -40°F |
| H-79 | 0.177 0.158 | 0.265 | 0.0444 | 241 | 10.70 | 0.892 | 155.5 | 0.053 | -40°F |
| H-83 | 0.177 0.157 | 0.266 | 0.0444 | 221 | 9.80 | 0.817 | 156.4 | 0.052 | -40°F |
| H-84 | 0.174 0.163 | 0.260 | 0.0438 | 244 | 10.70 | 0.892 | 155.5 | 0.058 | -40°F |
| H-90 | 0.177 0.159 | 0.275 | 0.0462 | 348 | 16.06 | 1.338 | 150.8 | 0.043 | -40°F |
| H-4 | 0.177 | 0.2441 | 0.0432 | 317 | 13.692 | 1.141 | 152.8 | | -40°F |
| H-9 | 0.174 | 0.2144 | 0.0373 | 354 | 13.212 | 1.101 | 153.2 | | -40°F |
| H-13 | 0.175 | 0.2401 | 0.0420 | 315 | 13.212 | 1.101 | 153.2 | | -40°F |
| H-19 | 0.176 | 0.2780 | 0.0489 | 366 | 17.88 | 1.49 | 149.3 | | -40°F |
| H-24 | 0.177 | 0.2889 | 0.0511 | 321 | 16.416 | 1.368 | 150.5 | | -40°F |
| H-39 | 0.174 | 0.2403 | 0.0418 | 367 | 15.336 | 1.278 | 151.4 | | -40°F |
| H-43 | 0.175 | 0.2204 | 0.0386 | 348 | 13.452 | 1.121 | 153.0 | | -40°F |
| H-46 | 0.171 | 0.2610 | 0.0446 | 323 | 14.388 | 1.199 | 152.2 | | -40°F |
| H-50 | 0.174 | 0.2542 | 0.0442 | 318 | 14.04 | 1.170 | 152.5 | | -40°F |
| H-54 | 0.174 | 0.2602 | 0.0453 | 381 | 17.28 | 1.44 | 149.8 | | -40°F |
| | | | | | | | | | |
| H-1 | 0.107 | 0.2531 | 0.0271 | 451 | 12.228 | 1.019 | 154.1 | | RT |
| H-2 | 0.106 | 0.2293 | 0.0243 | 419 | 10.188 | 0.849 | 156.0 | | RT |
| H-3 | 0.106 | 0.2442 | 0.0259 | 438 | 11.34 | 0.945 | 154.9 | | RT |
| H-6 | 0.176 | 0.2431 | 0.0428 | 479 | 20.52 | 1.71 | 147.2 | | RT |
| H-10 | 0.174 | 0.2385 | 0.0415 | 480 | 19.92 | 1.66 | 147.6 | | RT |

TABLE XLi (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D. | Test Temp. |
|--------------|-------|----------|--------|-------|--------|--------|---------|------|------------|
| H-21 | 0.176 | 0.2272 | 0.0400 | 465 | 18.60 | 1.55 | 148.7 | | RT |
| H-25 | 0.174 | 0.2466 | 0.0429 | 383 | 16.416 | 1.368 | 150.5 | | RT |
| H-28 | 0.100 | 0.2440 | 0.0244 | 496 | 12.108 | 1.009 | 154.2 | | RT |
| H-29 | 0.100 | 0.2590 | 0.0259 | 426 | 11.028 | 0.919 | 155.2 | | RT |
| H-30 | 0.100 | 0.2560 | 0.0256 | 478 | 12.228 | 1.019 | 154.1 | | RT |
| H-31 | 0.098 | 0.2582 | 0.0253 | 317 | 8.016 | 0.668 | 158.3 | | RT |
| H-32 | 0.101 | 0.2552 | 0.0258 | 531 | 13.692 | 1.141 | 152.8 | | RT |
| H-33 | 0.104 | 0.2591 | 0.0269 | 496 | 13.332 | 1.111 | 153.1 | | RT |
| H-40 | 0.172 | 0.2390 | 0.0411 | 534 | 21.96 | 1.83 | 146.1 | | RT |
| H-44 | 0.173 | 0.2280 | 0.0394 | 536 | 21.12 | 1.76 | 146.7 | | RT |
| H-47 | 0.168 | 0.2384 | 0.0401 | 296 | 11.88 | 0.990 | 154.4 | | RT |
| H-51 | 0.173 | 0.2541 | 0.0440 | 524 | 23.04 | 1.92 | 145.4 | | RT |
| H-55 | 0.173 | 0.2569 | 0.0444 | 492 | 21.84 | 1.82 | 146.2 | | RT |
| H-58 | 0.100 | 0.2084 | 0.0208 | 362 | 7.524 | 0.627 | 158.9 | | RT |
| H-59 | 0.100 | 0.2368 | 0.0237 | 302 | 7.152 | 0.596 | 159.3 | | RT |
| H-60 | 0.100 | 0.2228 | 0.0223 | 356 | 7.932 | 0.661 | 158.4 | | RT |
| H-61 | 0.098 | 0.2109 | 0.0207 | 324 | 6.708 | 0.559 | 159.8 | | RT |
| H-62 | 0.098 | 0.1641 | 0.0161 | 295 | 4.752 | 0.396 | 162.2 | | RT |
| H-63 | 0.097 | 0.2686 | 0.0261 | 298 | 7.776 | 0.648 | 158.6 | | RT |
| H-64 | 0.098 | 0.2062 | 0.0202 | 320 * | 6.468 | 0.539 | 160.1 | | RT |
| H-65 | 0.098 | 0.2564 | 0.0251 | 319 * | 8.016 | 0.668 | 158.3 | | RT |

*Crack propagating in the chamber hoop-direction.

TABLE XLI (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D. | Test Temp. |
|--------------|----------------|--------|--------|-------|--------|--------|---------|-------|------------|
| H-66 | 0.097 | 0.2486 | 0.0241 | 274 * | 6.612 | 0.551 | 159.9 | | RT |
| H-16 | 0.177 | | | | | | | | |
| H-17 | 0.177 | | | | | | | | |
| H-76 | 0.201 0.193 | 0.275 | 0.0542 | 268 | 14.50 | 1.208 | 152.1 | 0.043 | RT |
| H-80 | 0.202 0.184 | 0.252 | 0.0486 | 277 | 13.45 | 1.121 | 153.0 | 0.065 | RT |
| H-85 | 0.199 0.189 | 0.262 | 0.0508 | 295 | 14.98 | 1.248 | 151.7 | 0.057 | RT |
| H-88 | 0.199 0.186 | 0.217 | 0.0418 | 274 | 11.44 | 0.953 | 154.8 | 0.102 | RT |
| H-91 | 0.179 0.165 | 0.273 | 0.0470 | 702 | 33.00 | 2.75 | 139.1 | 0.047 | RT |
| | | | | | | | | | |
| H-70 | 0.177 0.167 | 0.249 | 0.0428 | 510 | 21.84 | 1.82 | 146.2 | 0.070 | 200°F |
| H-72 | 0.176 0.168 | 0.245 | 0.0421 | 516 | 21.72 | 1.81 | 146.3 | 0.075 | 200°F |
| H-77 | 0.176 0.163 | 0.123 | 0.0208 | 344 | 7.152 | 0.596 | 159.3 | 0.195 | 200°F |
| H-81 | 0.177 0.163 | 0.232 | 0.0394 | 383 | 15.10 | 1.258 | 151.6 | 0.088 | 200°F |
| H-86 | 0.174 0.164 | 0.227 | 0.0384 | 390 | 14.98 | 1.248 | 151.7 | 0.092 | 200°F |
| H-92 | 0.179 0.166 | 0.248 | 0.0428 | 642 | 27.48 | 2.29 | 142.5 | 0.071 | 200°F |
| H-94 | 0.178 0.168 | 0.268 | 0.0464 | 784 | 36.36 | 3.03 | 137.1 | 0.052 | 200°F |
| H-7 | 0.175 | 0.2246 | 0.0393 | 721 | 28.32 | 2.36 | 141.9 | | 200°F |
| H-11 | 0.174 | 0.2216 | 0.0386 | 634 | 24.48 | 2.04 | 144.4 | | 200°F |
| H-14 | 0.174 | 0.2384 | 0.0415 | 536 | 22.26 | 1.855 | 145.9 | | 200°F |
| H-22 | 0.174 | 0.2773 | 0.0483 | 701 | 33.84 | 2.82 | 138.6 | | 200°F |
| H-26 | 0.176 | 0.2194 | 0.0386 | 451 | 17.40 | 1.45 | 149.7 | | 200°F |

TABLE XLI (cont.)

| SPECIMEN NO. | WIDTH | DBN - cd | AREA | W/A | in. - lb | ft - lb | DEGREES | C.D. | Test Temp. |
|--------------|----------------|----------|--------|------|----------|---------|---------|-------|------------|
| H-41 | 0.174 | 0.2454 | 0.0427 | 811 | 34.62 | 2.885 | 138.1 | | 200°F |
| H-45 | 0.174 | 0.2567 | 0.0447 | 617 | 27.60 | 2.30 | 142.4 | | 200°F |
| H-48 | 0.171 | 0.2693 | 0.0461 | 657 | 30.30 | 2.525 | 140.7 | | 200°F |
| H-52 | 0.173 | 0.2379 | 0.0412 | 555 | 22.86 | 1.905 | 145.5 | | 200°F |
| H-56 | 0.173 | 0.2669 | 0.0462 | 644 | 29.76 | 2.48 | 141.0 | | 200°F |
| | | | | | | | | | |
| H-8 | 0.174 | 0.2289 | 0.0398 | 986 | 39.24 | 3.27 | 135.4 | | 320°F |
| H-12 | 0.175 | 0.2411 | 0.0422 | 894 | 37.74 | 3.145 | 136.3 | | 320°F |
| H-15 | 0.176 | 0.2387 | 0.0420 | 709 | 29.76 | 2.48 | 141.0 | | 320°F |
| H-23 | 0.175 | 0.2753 | 0.0482 | 957 | 46.14 | 3.845 | 131.7 | | 320°F |
| H-27 | 0.173 | 0.2358 | 0.0408 | 606 | 24.72 | 2.06 | 144.2 | | 320°F |
| H-42 | 0.173 | 0.2381 | 0.0412 | 836 | 34.44 | 2.87 | 138.2 | | 320°F |
| H-49 | 0.172 | 0.2650 | 0.0456 | 989 | 45.12 | 3.76 | 132.2 | | 320°F |
| H-53 | 0.173 | 0.2659 | 0.0460 | 1424 | 65.52 | 5.46 | 122.1 | | 320°F |
| H-57 | 0.172 | 0.2083 | 0.0358 | 560 | 20.04 | 1.67 | 147.5 | 0.186 | 320°F |
| H-71 | 0.177 0.164 | 0.225 | 0.0384 | 725 | 27.84 | 2.32 | 142.3 | 0.093 | 320°F |
| H-73 | 0.176 0.165 | 0.269 | 0.0459 | 918 | 42.12 | 3.51 | 133.9 | 0.050 | 320°F |
| H-74 | 0.176 0.164 | 0.245 | 0.0417 | 927 | 38.64 | 3.22 | 135.9 | 0.072 | 320°F |
| H-78 | 0.177 0.158 | 0.267 | 0.0447 | 784 | 35.04 | 2.92 | 137.9 | 0.053 | 320°F |
| H-82 | 0.178 0.158 | 0.238 | 0.0400 | 642 | 25.68 | 2.14 | 143.6 | 0.080 | 320°F |
| H-87 | 0.175 0.159 | 0.261 | 0.0436 | 906 | 39.48 | 3.29 | 135.3 | 0.058 | 320°F |

TABLE XLII

PRECRACK CHARPY IMPACT DATA - 6A1-4V TITANIUM

| Minuteman Chamber S/N | Specimen Location | Wall Thickness | Test Temperature, °F | | |
|--------------------------|------------------------------------|-------------------|-------------------------|-------------------------|--------------------------|
| | | | -40 | RT | 200 |
| 2192109 | Fwd Skirt | 0.113 | | 481 - 508 Avg(3) 498 | |
| | Fwd Closure | 0.113 | | 413 - 493 Avg(3) 461 | |
| | G1 reinforced section | 0.185 | 269 - 349 Avg(3) 319 | 422 - 532 Avg(3) 474 | 887 - 1019 Avg(3) 947 |
| | Fwd Cyl | 0.185 | 220 - 315 Avg(3) 279 | 332 - 400 Avg(2) 366 | 415 - 450 Avg(3) 438 |
| | 2-in. aft of G1 weld | 0.107 | | 289 - 387 Avg(3) 331 | |
| | Near hoop- fracture junction | 0.105 | | 242 - 276 Avg(3) 263 | |
| | Ditto, Hoop direction | 0.106 | | 340 - 381 Avg(3) 365 | |

TABLE XLIII

PRECRACK CHARPY IMPACT DATA
MINUTEMAN CHAMBER 2192109 (52-IN.DIA)

| <u>Component</u> | <u>Specimen No.</u> |
|------------------|---------------------|
| Forward Skirt | K1 - 3 |
| Forward Closure | K4 - 18 |
| Forward Cylinder | |
| At G1 Weld | K19 - 33 |
| At G2 Weld | K34 - 39* |
| Aft Cylinder | |
| At G2 Weld | - |
| At G3 Weld | - |
| Aft Closure | - |
| Aft Skirt | - |

*Specimens located at intersection of
primary axial fracture and secondary
hoop fracture.

TABLE XLIII (cont.)

| SPECIMEN NO. | WIDTH | DBN-cd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C.D | Test Temp. |
|-----------------|----------------|--------|--------|-----|--------|--------|---------|-------|---------------|
| K-7 | 0.185 0.170 | 0.287 | 0.0509 | 269 | 13.69 | 1.141 | 152.8 | 0.031 | -40°F |
| K-11 | 0.190 0.177 | 0.270 | 0.0495 | 349 | 17.28 | 1.44 | 149.8 | 0.050 | -40°F |
| K-15 | 0.191 0.179 | 0.270 | 0.0500 | 340 | 17.02 | 1.418 | 150.0 | 0.048 | -40°F |
| K-19 | 0.189 0.181 | 0.279 | 0.0516 | 220 | 11.34 | 0.945 | 154.9 | 0.029 | -40°F |
| K-23 | 0.193 0.187 | 0.274 | 0.0521 | 315 | 16.42 | 1.368 | 150.5 | 0.045 | -40°F |
| K-27 | 0.193 0.185 | 0.287 | 0.0542 | 301 | 16.30 | 1.358 | 150.6 | 0.032 | -40°F |
| | | | | | | | | | |
| K-1 | 0.112 | 0.272 | 0.0304 | 481 | 14.62 | 1.218 | 152.0 | 0.046 | RT |
| K-2 | 0.113 | 0.265 | 0.0299 | 505 | 15.10 | 1.258 | 151.6 | 0.054 | RT |
| K-3 | 0.113 | 0.280 | 0.0316 | 508 | 16.06 | 1.338 | 150.8 | 0.040 | RT |
| K-4 | 0.113 | 0.275 | 0.0311 | 493 | 15.34 | 1.278 | 151.4 | 0.046 | RT |
| K-5 | 0.113 | 0.262 | 0.0296 | 413 | 12.23 | 1.019 | 154.1 | 0.057 | RT |
| K-6 | 0.113 | 0.262 | 0.0296 | 478 | 14.15 | 1.179 | 152.4 | 0.054 | RT |
| K-8 | 0.188 0.176 | 0.284 | 0.0517 | 532 | 27.48 | 2.29 | 142.5 | 0.032 | RT |
| K-12 | 0.190 0.180 | 0.255 | 0.0472 | 422 | 19.92 | 1.66 | 147.6 | 0.064 | RT |
| K-16 | 0.191 0.181 | 0.261 | 0.0485 | 468 | 22.68 | 1.89 | 145.6 | 0.060 | RT |
| K-20 | 0.190 0.183 | 0.155 | 0.0289 | 217 | 6.28 | 0.523 | 160.3 | 0.164 | RT |
| K-24 | 0.188 | 0.258 | 0.0486 | 400 | 19.44 | 1.62 | 148.1 | 0.060 | RT |
| K-28 | 0.192 0.184 | 0.266 | 0.0501 | 332 | 16.64 | 1.387 | 150.3 | 0.052 | RT |
| K-31 | 0.105 | 0.267 | 0.0280 | 289 | 8.10 | 0.675 | 158.2 | 0.053 | RT |
| K-32 | 0.107 | 0.266 | 0.0285 | 387 | 11.03 | 0.919 | 155.2 | 0.052 | RT |

TABLE XLIII (cont.)

| SPECIMEN NO. | WIDTH | DBN - sd | AREA | W/A | in.-lb | ft.-lb | DEGREES | C D. | Test Temp. |
|--------------|----------------|----------|--------|-------|--------|--------|---------|-------|------------|
| K-33 | 0.108 | 0.258 | 0.0279 | 316 | 8.81 | 0.734 | 157.4 | 0.061 | RT |
| K-34 | 0.104 | 0.231 | 0.0240 | 242 | 5.80 | 0.483 | 160.9 | 0.088 | RT |
| K-35 | 0.105 | 0.265 | 0.0278 | 276 | 7.68 | 0.640 | 158.7 | 0.054 | RT |
| K-36 | 0.105 | 0.270 | 0.0284 | 270 | 7.68 | 0.640 | 158.7 | 0.049 | RT |
| K-37 | 0.106 | 0.279 | 0.0296 | 373 * | 11.03 | 0.919 | 155.2 | 0.040 | RT |
| K-38 | 0.106 | 0.268 | 0.0284 | 381 * | 10.81 | 0.901 | 155.4 | 0.052 | RT |
| K-39 | 0.106 | 0.277 | 0.0294 | 340 * | 10.00 | 0.833 | 156.2 | 0.040 | RT |
| | | | | | | | | | |
| K-9 | 0.189 0.180 | 0.257 | 0.0474 | 595 | 28.20 | 2.35 | 142.0 | 0.062 | 200°F |
| K-13 | 0.190 0.182 | 0.225 | 0.0419 | 558 | 23.40 | 1.95 | 145.1 | 0.095 | 200°F |
| K-17 | 0.191 0.182 | 0.249 | 0.0464 | 499 | 23.16 | 1.93 | 145.3 | 0.071 | 200°F |
| K-21 | 0.192 0.184 | 0.230 | 0.0432 | 450 | 19.44 | 1.62 | 148.1 | 0.089 | 200°F |
| K-25 | 0.194 0.187 | 0.225 | 0.0429 | 448 | 19.20 | 1.60 | 148.3 | 0.094 | 200°F |
| K-29 | 0.192 0.186 | 0.203 | 0.0384 | 415 | 15.94 | 1.328 | 150.9 | 0.115 | 200°F |
| | | | | | | | | | |
| K-10 | 0.190 0.180 | 0.277 | 0.0512 | 1019 | 52.2 | 4.35 | 128.2 | 0.041 | 320°F |
| K-14 | 0.191 0.176 | 0.252 | 0.0462 | 887 | 41.0 | 3.42 | 134.5 | 0.064 | 320°F |
| K-18 | 0.191 0.179 | 0.261 | 0.0483 | 934 | 45.1 | 3.76 | 132.2 | 0.058 | 320°F |
| K-22 | 0.193 0.180 | 0.231 | 0.0431 | 768 | 33.1 | 2.76 | 139.0 | 0.088 | 320°F |
| K-26 | 0.193 0.188 | 0.238 | 0.0453 | 715 | 32.4 | 2.70 | 139.4 | 0.079 | 320°F |
| K-30 | 0.193 0.182 | 0.240 | 0.0450 | 691 | 31.1 | 2.59 | 140.2 | 0.077 | 320°F |

*Crack propagating in the chamber hoop-direction.

APPENDIX II

TRANSITION CURVES
(W/A vs TEMPERATURE)

6Al-4V Titanium 160 ksi Yield Strength
39 ksi-in.^{1/2} Plane-Strain Fracture Toughness

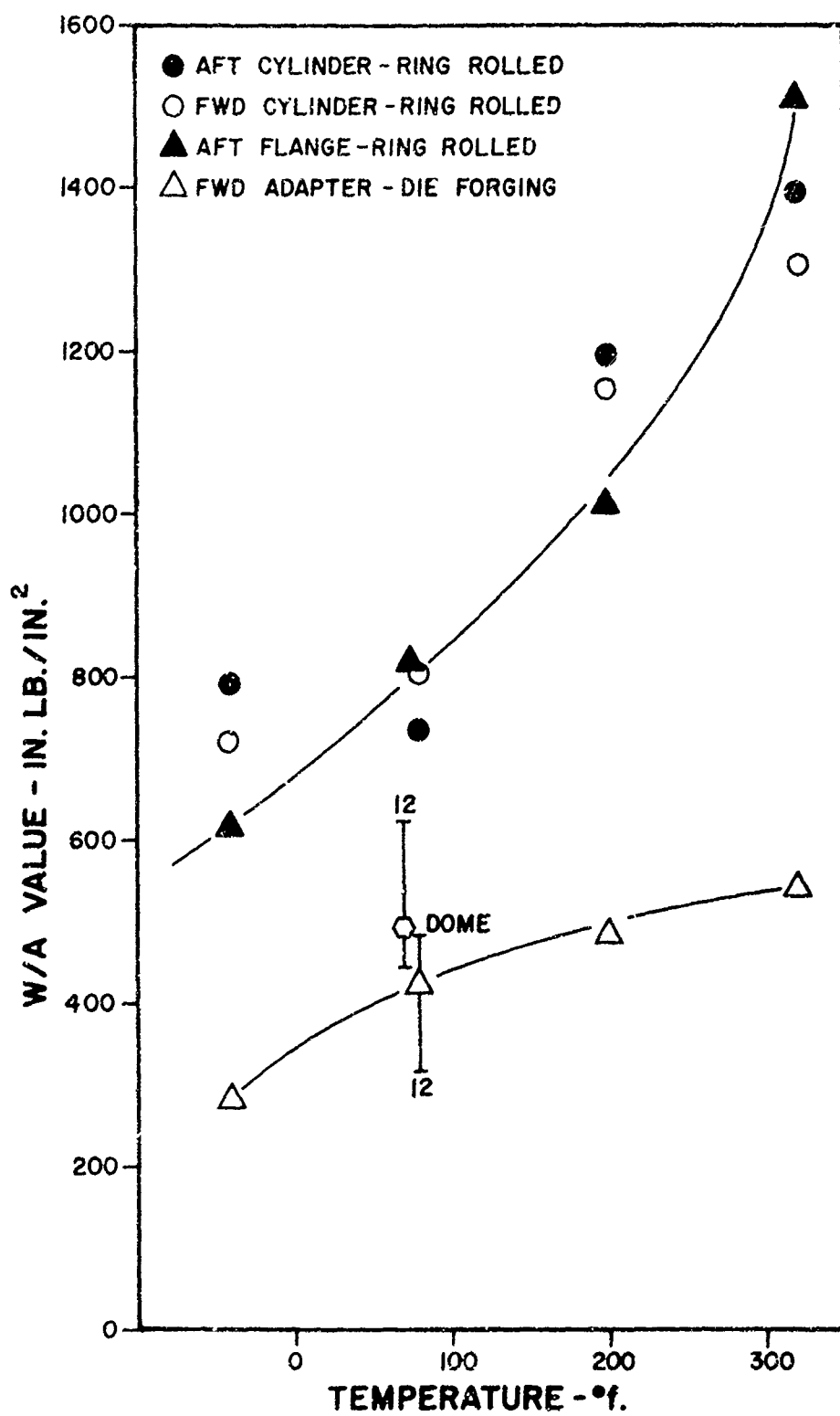


Figure 25. Chamber R26

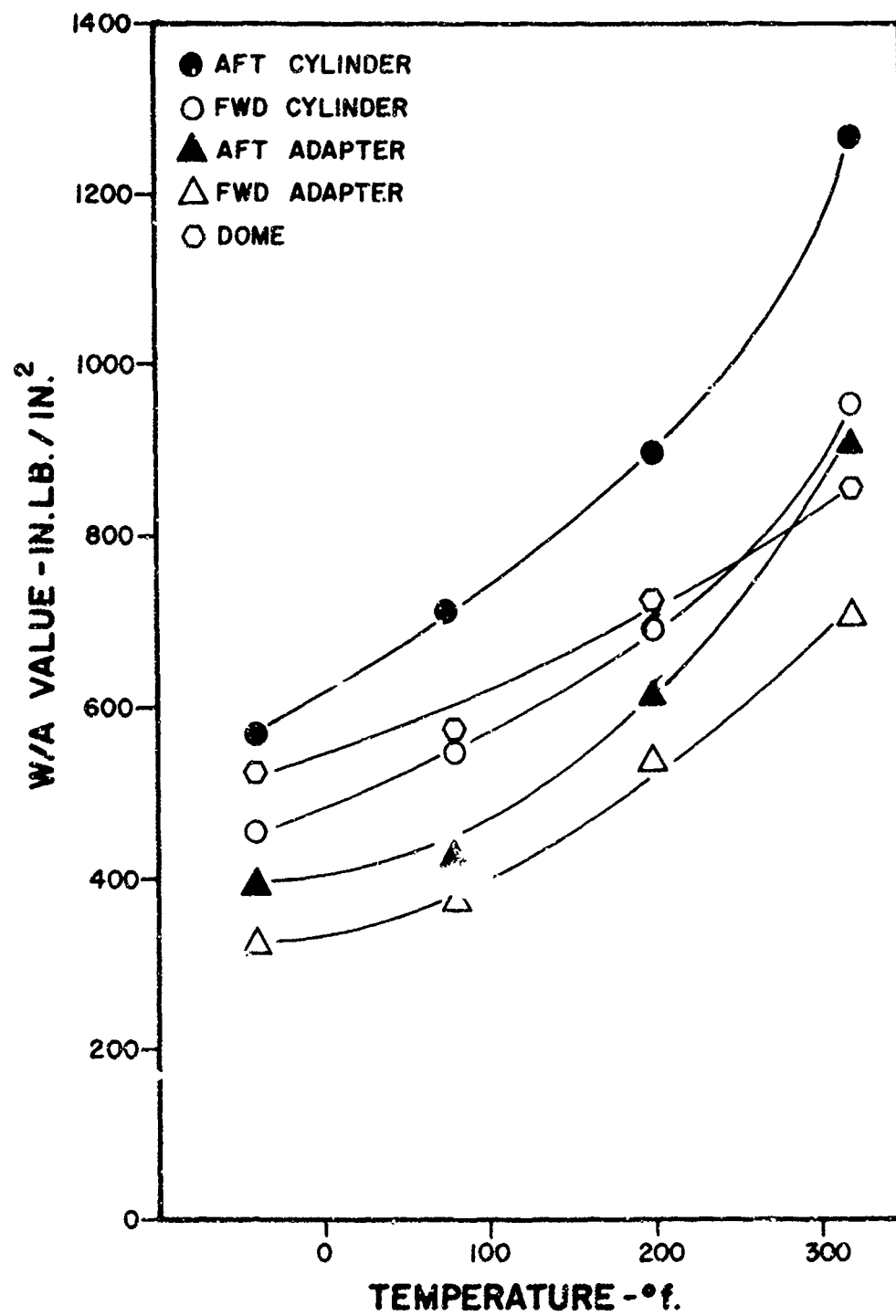


Figure 26. Chamber R41

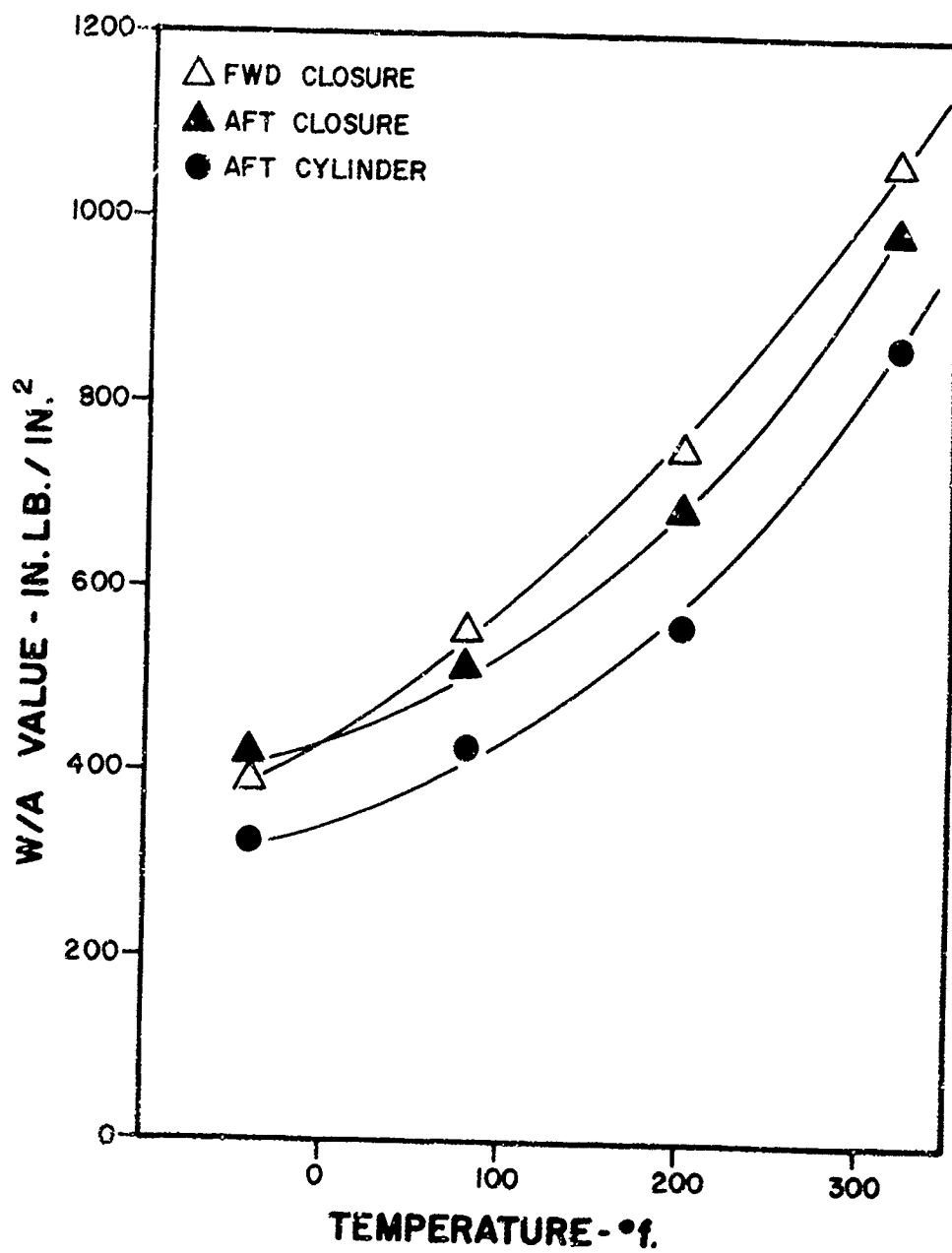


Figure 27. Chamber BL26

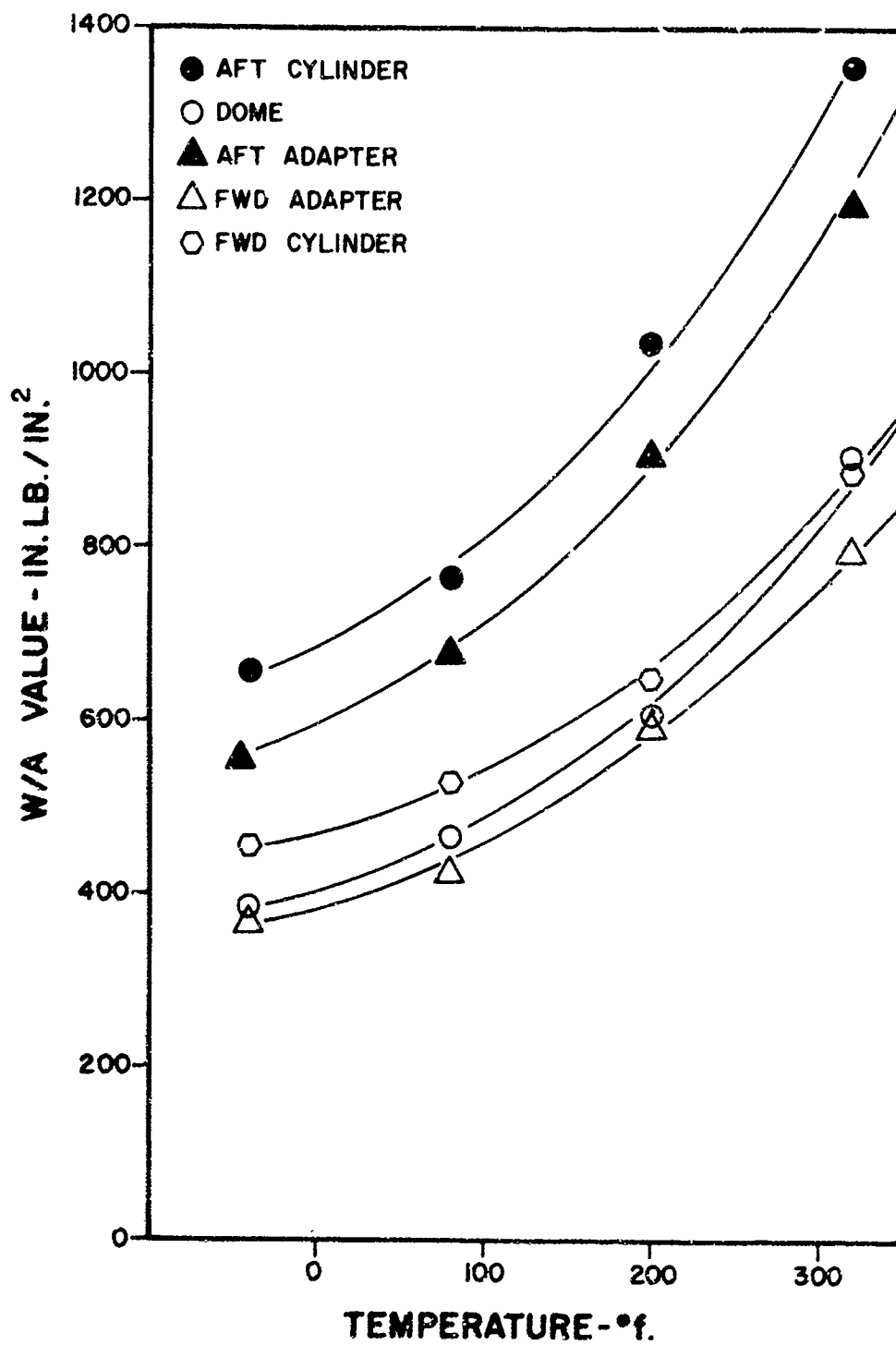


Figure 28. Chamber 2191456

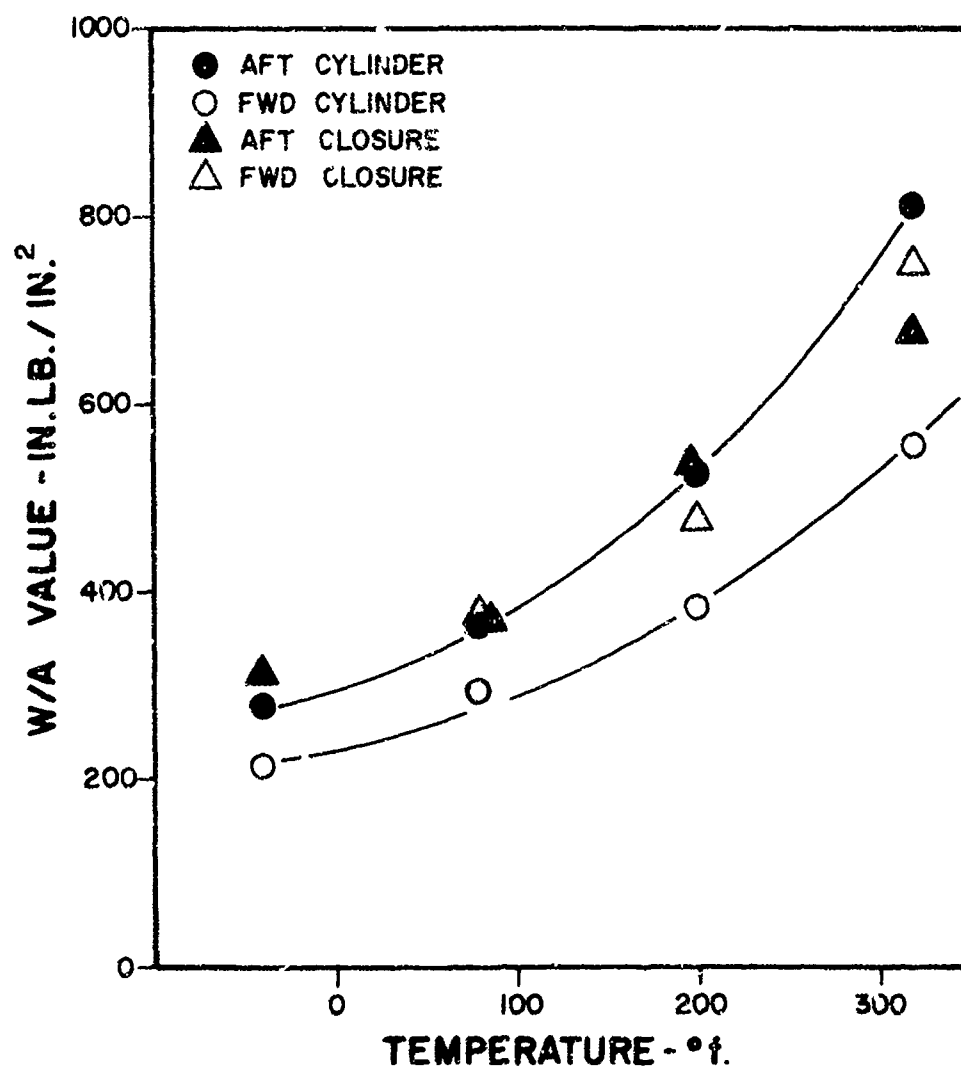


Figure 29. Chamber R369

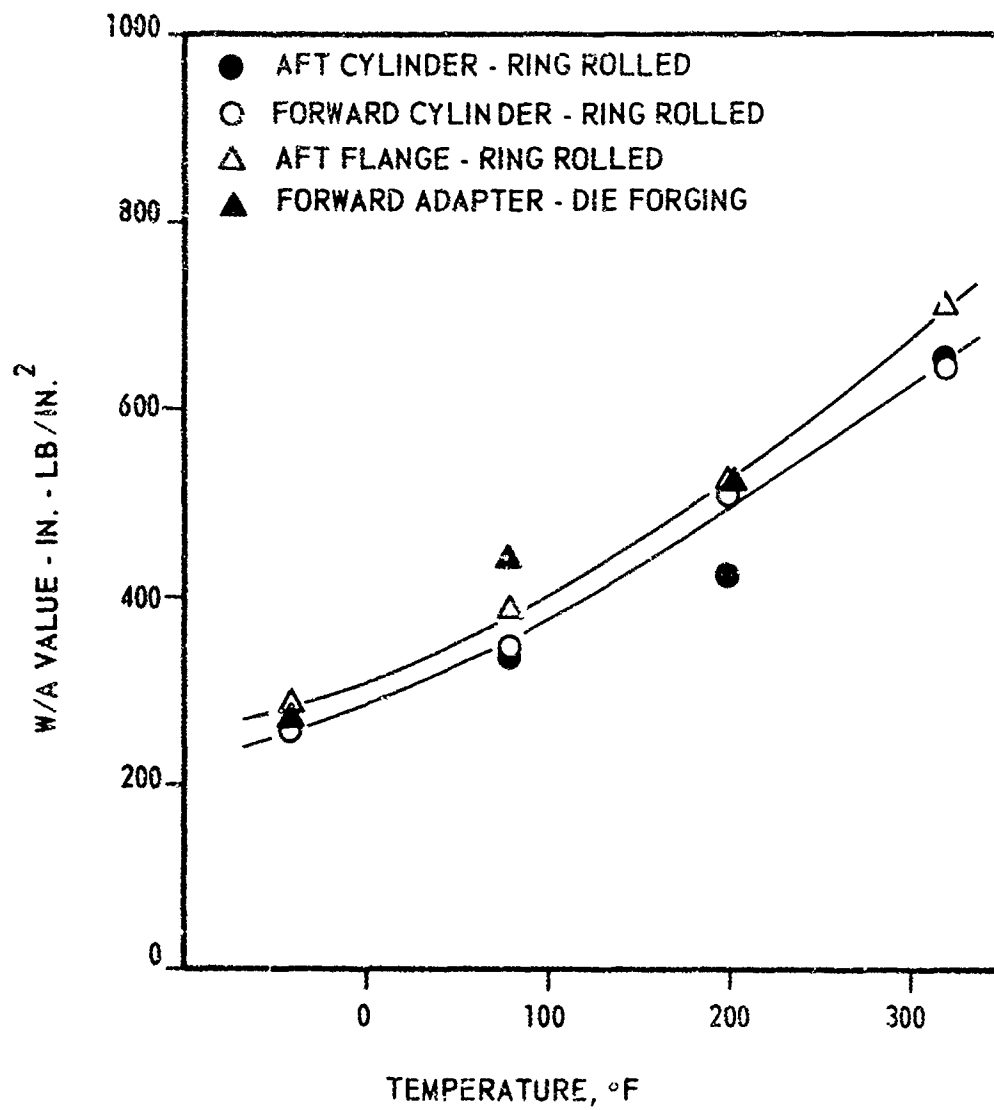


Figure 30. Chamber R490

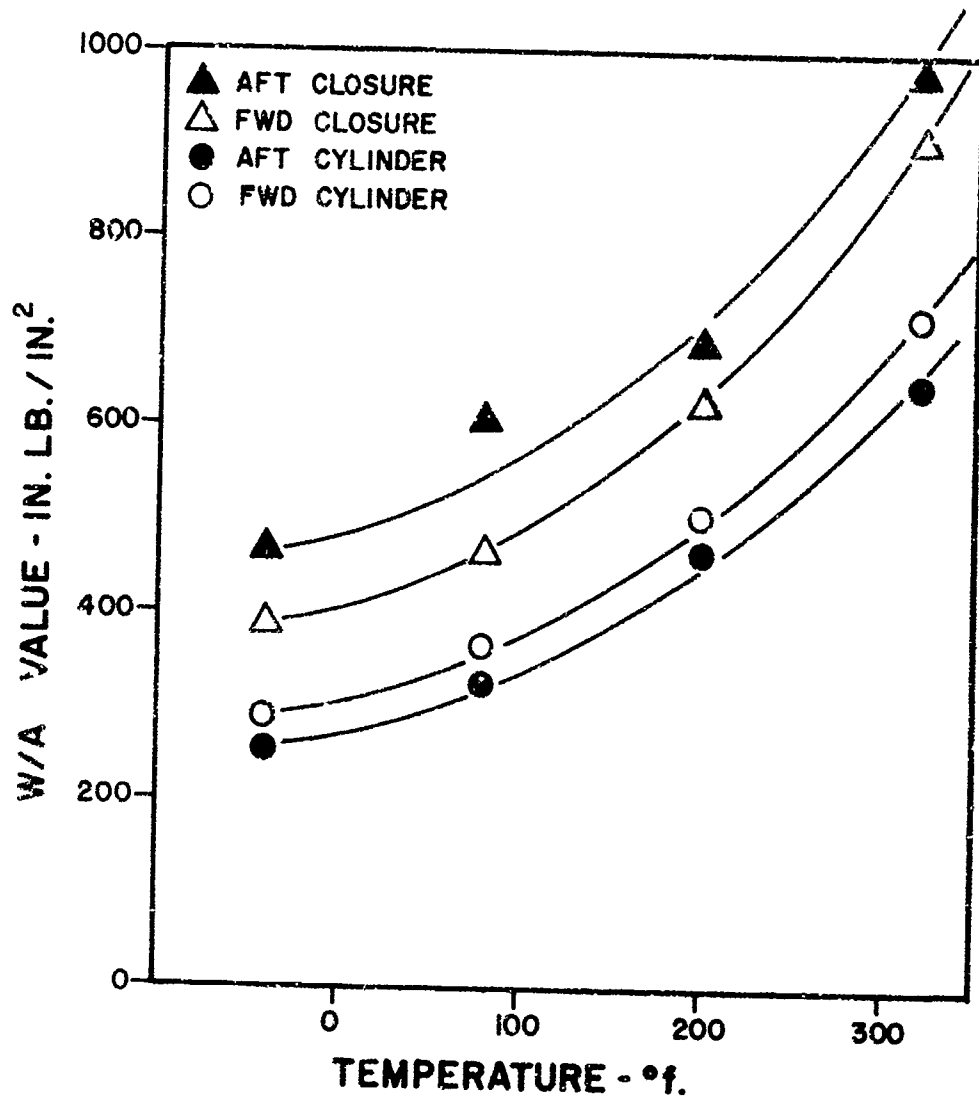


Figure 31. Chamber R512

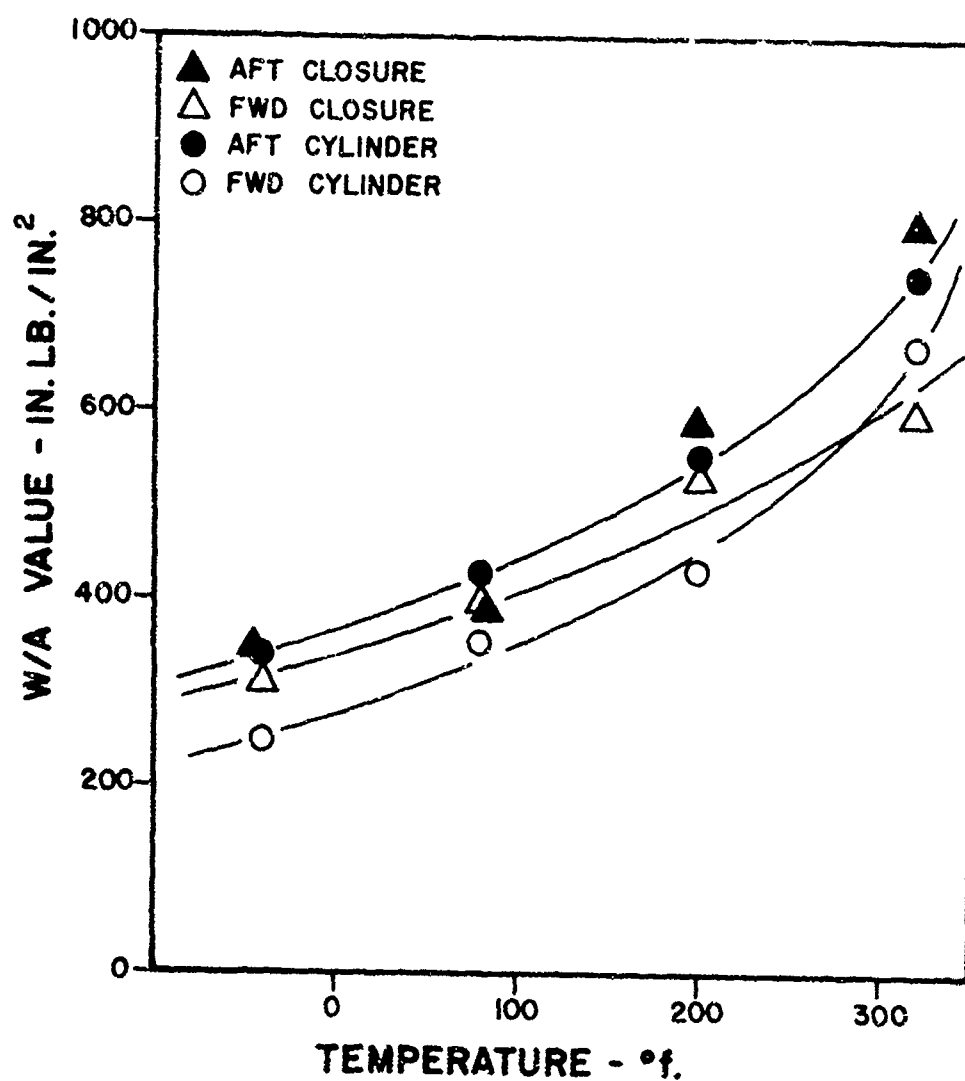


Figure 32. Chamber R516

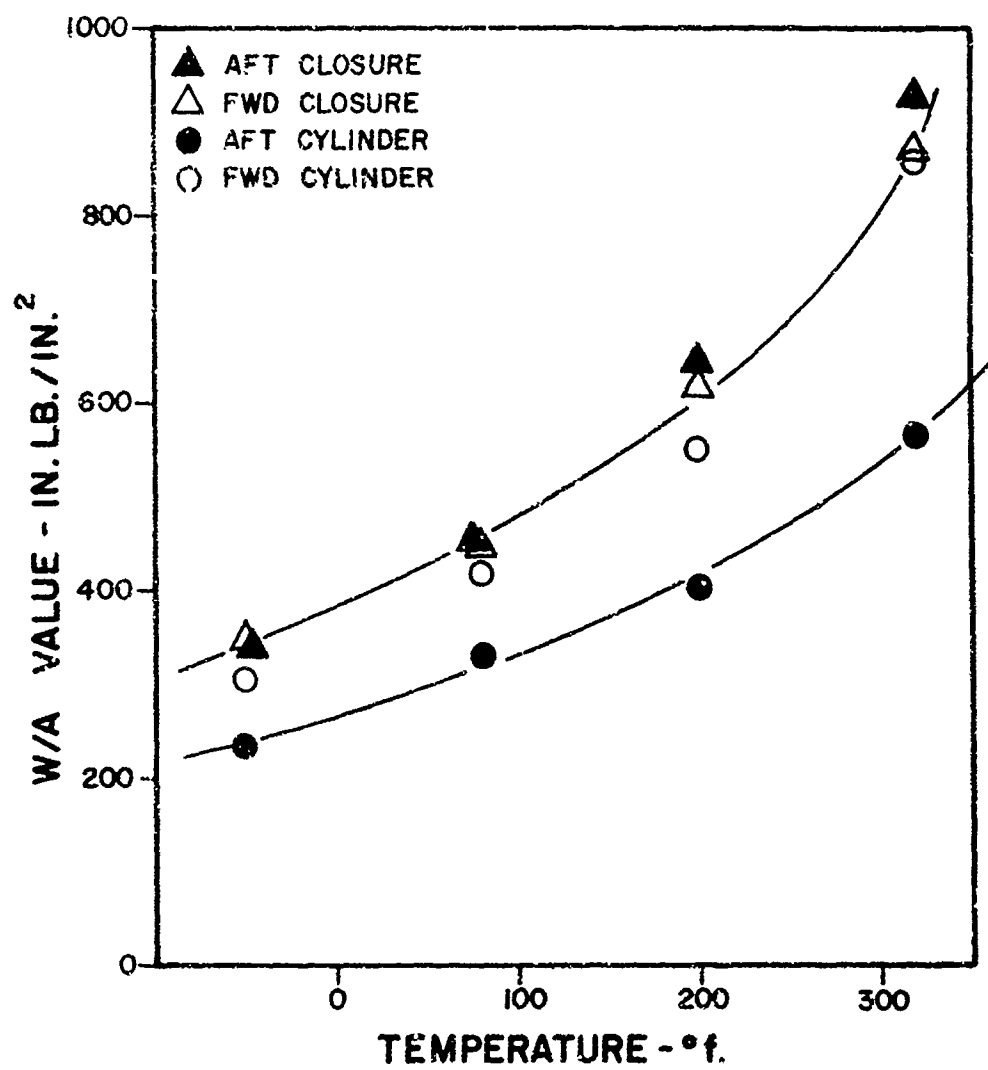


Figure 33. Chamber R543

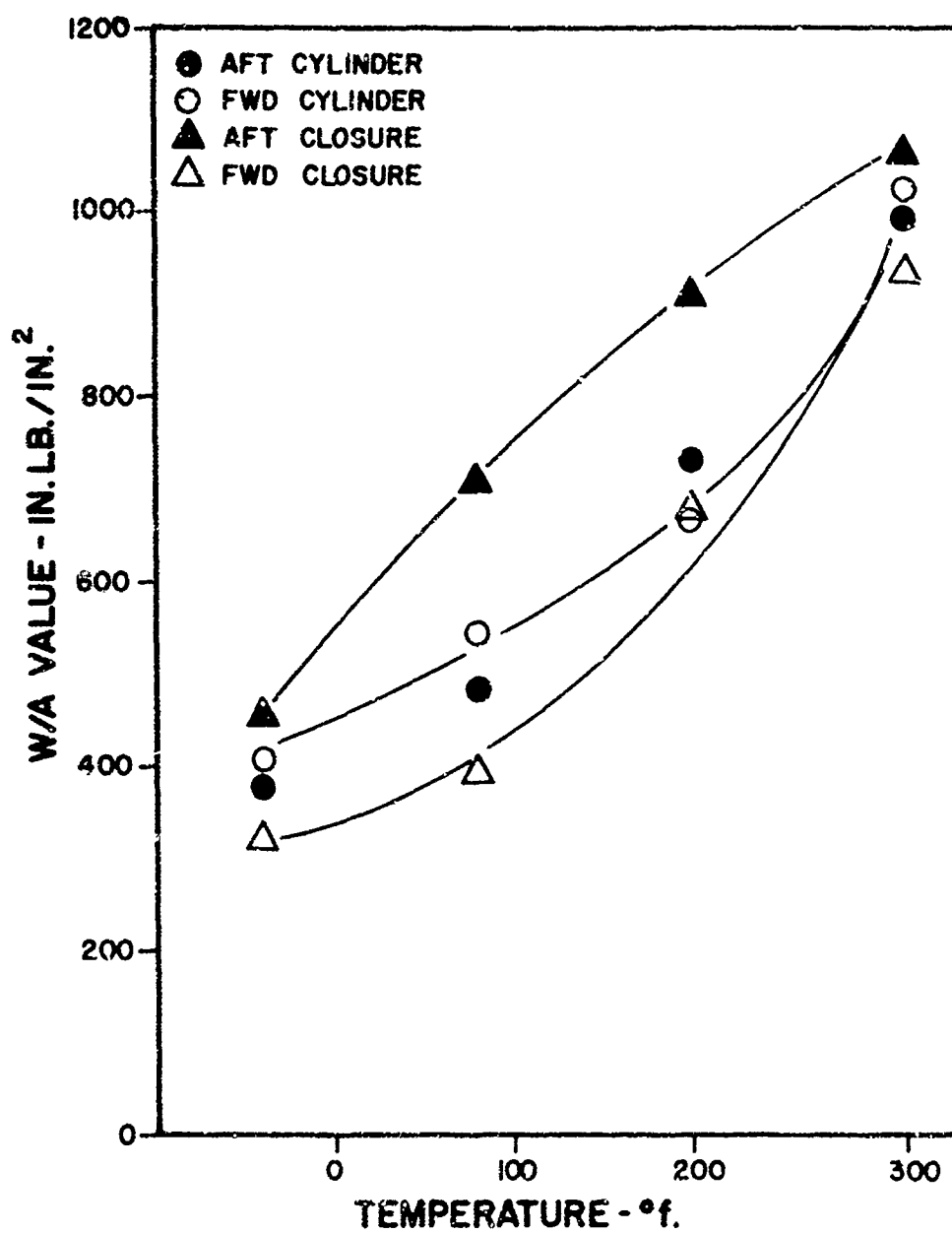
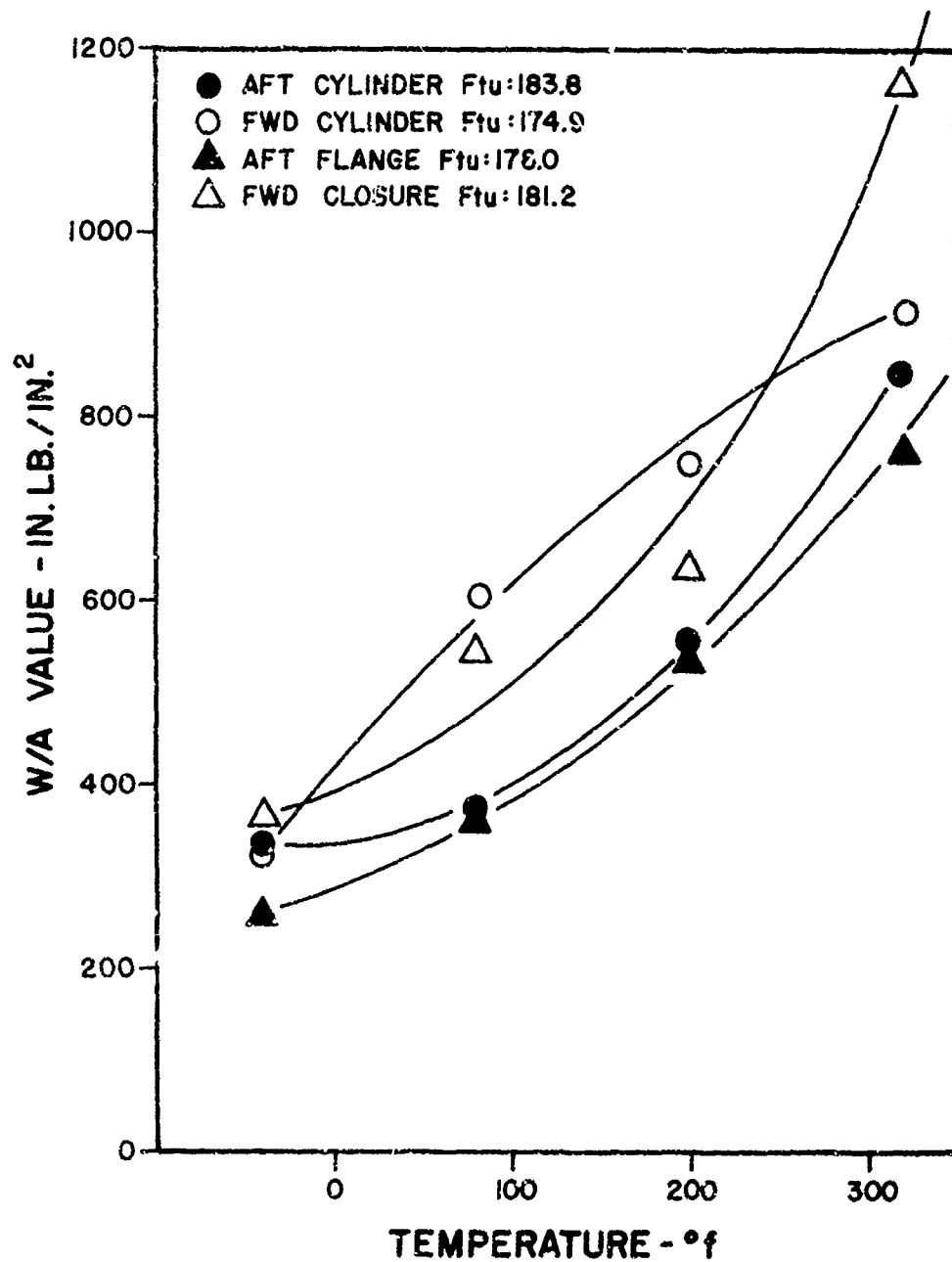


Figure 34. Chamber 673078



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Figure 35. Chamber 673095

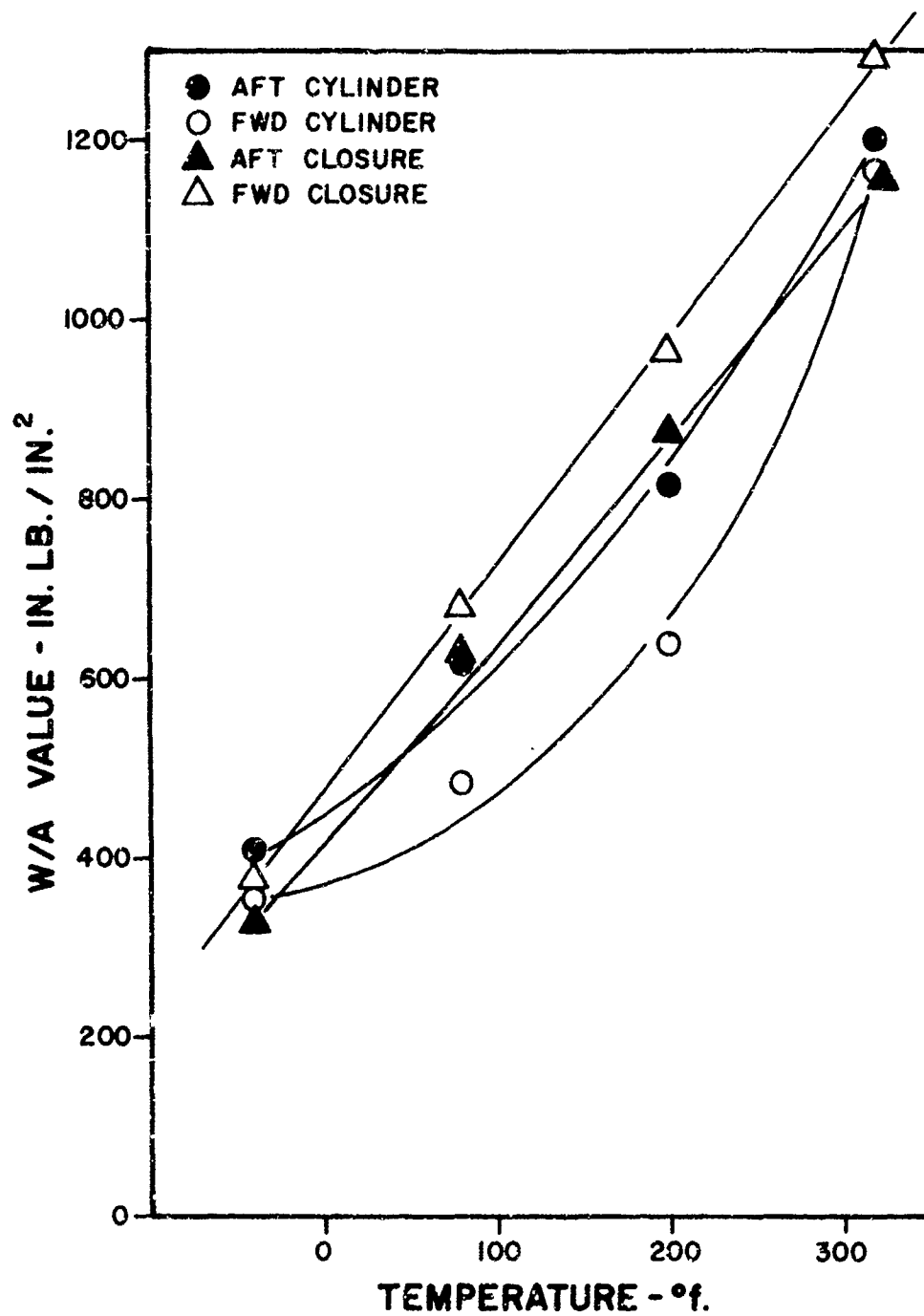


Figure 36. Chamber 673122

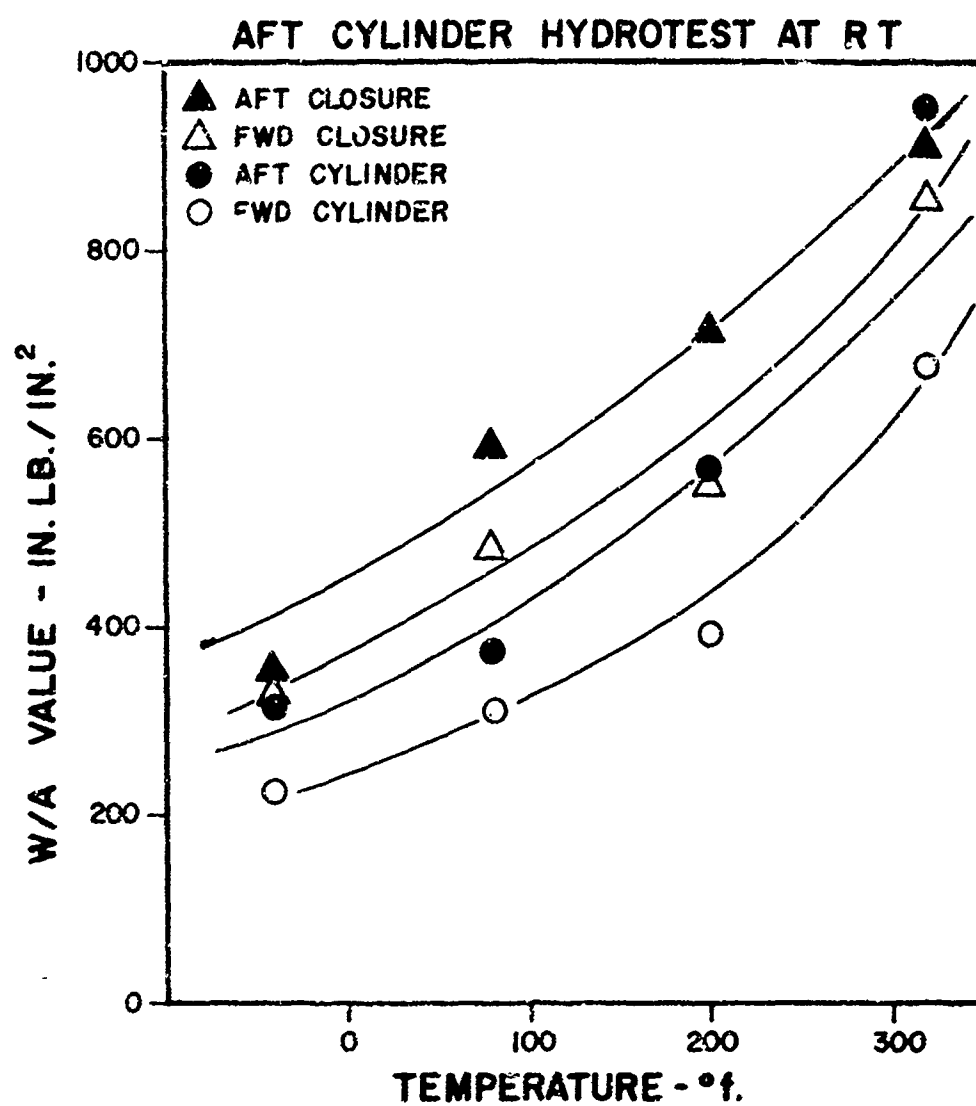


Figure 37. Chamber 674514

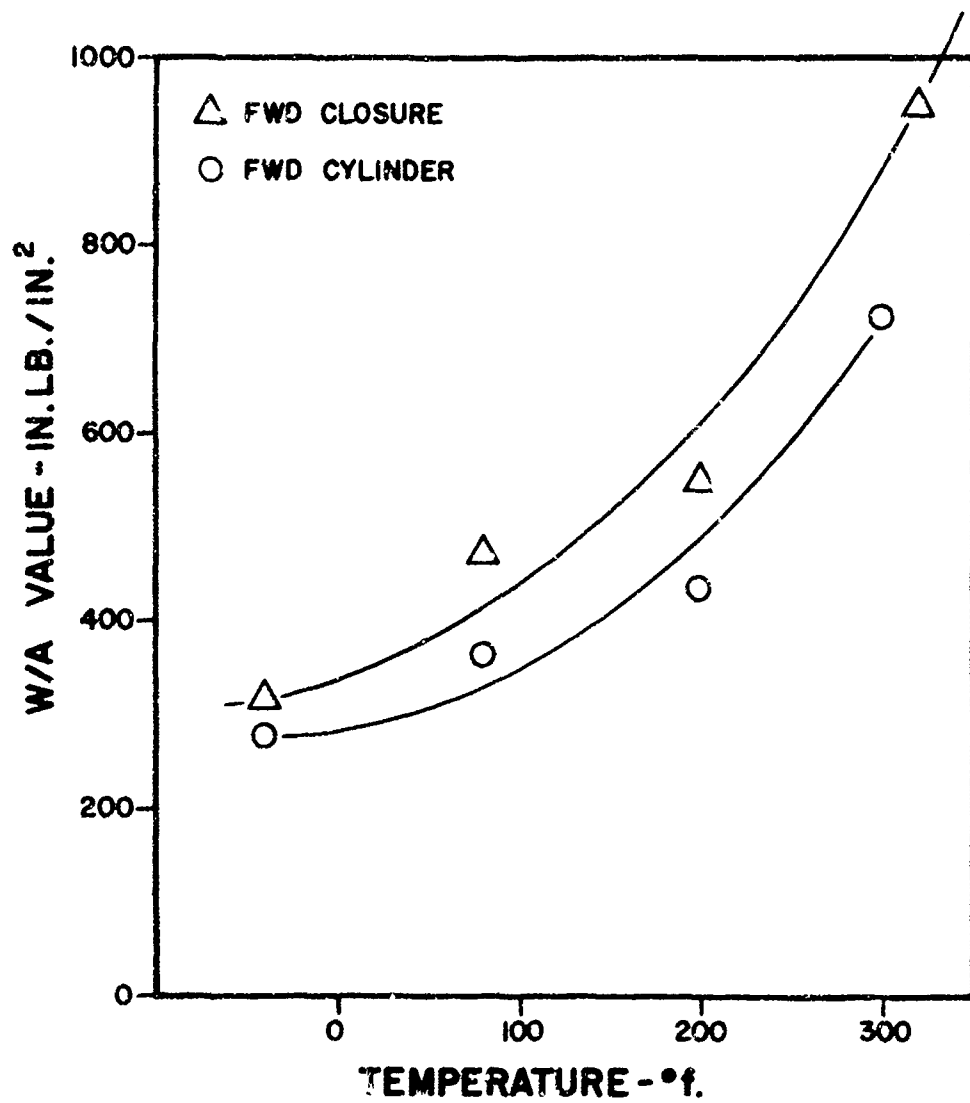


Figure 38. Chamber 2192109

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